An Early-Stage Decision-Support Framework for the Implementation of Intelligent Automation

by
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Abstract

The constant pressure on manufacturing companies to improve productivity, reduce the lead time and progress in quality requires new technological developments and adoption.

The rapid development of smart technology and robotic and autonomous systems (RAS) technology has a profound impact on manufacturing automation and might determine winners and losers of the next generation's manufacturing competition. Simultaneously, recent smart technology developments in the areas enable an automation response to new production paradigms such as mass customisation and product-lifecycle considerations in the context of Industry 4.0. New paradigms, like mass customisation, increased both the complexity of the tasks and the risk due to smart technology integration. From a manufacturing automation perspective, intelligent automation has been identified as a possible response to arising demands. The presented research aims to support the industrial uptake of intelligent automation into manufacturing businesses by quantifying risks at the early design stage and business case development. An early stage decision-support framework for the implementation of intelligent automation in manufacturing businesses is presented in this thesis.

The framework is informed by an extensive literature review, updated and verified with surveys and workshops to add to the knowledge base due to the rapid development of the associated technologies. A paradigm shift from cost to a risk-modelling perspective is proposed to provide a more flexible and generic approach applicable throughout the current technology landscape. The proposed probabilistic decision-support framework consists of three parts:

- A clustering algorithm to identify the manufacturing functions in manual processes from a task analysis to mitigate early-stage design uncertainties
- A Bayesian Belief Network (BBN) informed by an expert elicitation via the DELPHI method, where the identified functions become the unit of analysis.
- A Markov-Chain Monte-Carlo method modelling the effects of uncertainties on the critical success factors to address issues of factor interdependencies after expert elicitation.

Based on the overall decision framework a toolbox was developed in Microsoft Excel. Five different case studies are used to test and validate the framework. Evaluation of the results derived from the toolbox from the industrial feedback suggests a positive validation for commercial use. The main contributions to knowledge in the presented thesis arise from the following four points:

- Early-stage decision-support framework for business case evaluation of intelligent automation.
- Translating manual tasks to automation function via a novel clustering approach
- Application of a Markov-Chain Monte-Carlo Method to simulate correlation between decision criteria
- Causal relationship among Critical Success Factors has been established from business and technical perspectives.

The implications on practise might be promising. The feedback arising from the created tool was promising from the industry, and a practical realisation of the decision-support tool seems to be desired from an industrial point of view.

With respect to further work, the decision-support tool might have established a ground to analyse a human task automatically for automation purposes. The established clustering mechanisms and the related attributes could be connected to sensorial data and analyse a manufacturing task autonomously without the subjective input of task analysis experts. To enable such an autonomous process, however, the psychophysiological understanding must be increased in the future.

Dedication

In memory of my grandfather
Max Vetter,
And
To my beloved parents
Hermann and Karin Micheler

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List of Publications

Conference Paper

Micheler, S., Goh, Y. M., & Lohse, N. (2016). Influencing factors for implementing automation in manufacturing businesses–a literature review. *Proceedings of the 14th International Conference on Manufacturing Research (ICMR)*, September 2016.

Green Paper

Green paper: R&D Priorities for Smart Manufacturing Components and Systems. Programme: H2020-FoF-2014. Project No.: 637178. Project-Acronym: Co-FACTOR. 17.02.2017.

Journal Paper:

Micheler, S., Goh, Y. M., Sanchez-Salas, A., Case, K. (2018). A variability taxonomy to support automation decision-making for manufacturing processes. *Production Planning & Control. The Management of Operations.* Corrections submitted 15/03/2019.

Micheler, S., Goh, Y. M., & Lohse, N. (2019). Opportunities and Challenges for Smart Technologies and Systems in Manufacturing – A European Perspective. *International Journal of Production and Manufacturing Research.* Submitted 15/03/2019

Micheler, S., Goh, Y. M., & Lohse, N. (2019). A Transformation of Human Operation Approach to Inform System Design for Automation. *International Journal of Intelligent Manufacturing*. Submitted 16/03/2019.

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Glossary List

Action	Accumulated inseparable activities described by a single verb key to successfully finish an operation. Action is the lowest level of the division for a task/process analysis.
Attribute	A specification or piece of information determining properties of an entity. A property is a variable characteristic of an entity. In this thesis primarily used to describe characteristics of manufacturing operations.
Automation	A hardware and software system (or device) that executes a manufacturing function previously accomplished by humans.
Bayesian Network	A probabilistic graphical model with a set of variables and dependencies through use of a directed, yet noncyclic graph.
Critical Success Factor	A Critical Success Factor (CSF) is a variable, event or a circumstance required to ensure the desired outcome for an automation project.
Decision	A conclusion or determination of a specific action, event, outcome, or consequence reached after reflection.
Decision-Making	The act or process of deciding.
Dependence	State of relying on, being influenced, controlled, or affected by something. In this thesis dependencies are described between the critical success factors identified through expert elicitation.

Design	Determination and/or decision upon the functioning of an object or system by producing a specification.
Expert Elicitation	The formalised and documented procedure for expert knowledge extraction
Function	A function is a set of specific activities natural to or the purpose of a process, working in a particular way.
Hierarchical Task Analysis	A structured, objective and hierarchical approach to describing an operator's performance of tasks to achieve the desired outcome.
Data	Quantitative and qualitative recorded facts or statistics based on current or historical events.
Information	Accumulated and structured data subject to decision-making and knowledge demand.
Intelligent Automation	Automation embracing advanced sensing, decision-making, and actuation (i.e. smart technology) to form highly adaptive automation systems in manufacturing.
Markov-Chain Monte-Carlo	Technique for estimating an expectation of a complex statistic model by simulation, often based on successive random selections of estimated distributions.
Model	A simplified representation of a complex reality. The simplification reduces the reality, where not every attribute of

the original is taken into consideration but only attributes subject to the domain.

Operation Set of accumulated inseparable actions, performed in sequence or parallel, required to complete a task.

Perception The use of sensors or senses to collect data from a specific environment transformable into information.

Probability The extent to which a specific action, event, outcome, or consequence is likely to occur or be the case.

Process A process is a purposeful course of activities physically and/or chemically transforming inputs to outputs and adding value through alteration.

Process Variability

Risk An exposure to the consequences of uncertainty, and its consequence considered an undesirable outcome that can be identified and quantified through impact and likelihood.

Smart Technology Key enabler, building blocks and atomic elements, which serve as the technical basis for smart manufacturing systems with the capability to sense, communicate, aggregate and analyse information and to act in an optimized, self-adapted and self-aware manner.

Standard Operating Procedure A manufacturers' set of rules and instructions that must be followed to conduct a manufacturing process.

Subjective Probability	The extent to which a specific action, event, outcome, or consequence is thought (by an expert/individuum)to be likely to occur or be the case.
Task	Tasks consist of parallel or in sequence performed set of operations accumulated to satisfy a process function transforming inputs into outputs.
Text Mining	Extraction and analysis of large amount of text data to collect information, typically derived through formulating patterns and trends via statistical methods aided by software.
Uncertainty	Lack of knowledge subject to time about the involved variables, states and their outcome characterising a physical system.

1 Introduction

"The progressive integration of new technologies in our economy amounts to a paradigm shift with a profound impact on the context and content of work" – Alexander De Croo

Fundamentally, every manufacturing industry must optimise their product quality and reduce lead time to deliver parts on time, at reasonable costs, and to gain customer's confidence [1]. In the global economy, the term Industry 4.0, also known as smart manufacturing, has become a popular term to describe a paradigm within the manufacturing environment. A UK Foresight report from the Government Office for Science identified several key drivers for a faster and more responsive way of manufacturing closer to the customer (mass customisation, personalisation) [2]. The idea behind those enabling technologies, related to Industry 4.0, is the interconnection of industrial production systems using digital communication and information technologies to enhance intelligence and digitally connected systems [3]. The interconnection of production systems is expected to enable optimisation within the whole production and supply chain from cradle to grave (product life-cycle considerations) [4].

1.1 Robotics and Autonomous Systems and Smart Manufacturing

The latest developments in Robotics and Autonomous Systems (RAS) are expected to lead to a transformation of future production systems' capabilities and productivity [5]. RAS is a more general research domain, which is mostly concerned about fundamental developments in robotics. Related research in RAS extends the state-of-the-art in both symbolic and sensory-based robot control and learning in the context of autonomous systems [6]. The focus appears to be more on robotic and autonomous control system developments rather than on manufacturing. Even though the developments are in a cross-disciplinary sub-field of artificial intelligence, robotics, and information engineering, the RAS developments have an enabling impact on automation systems as novel control mechanisms allow more flexible reactions to process variability.

An increased human-robot collaboration, as well as higher degrees of autonomy within an automation system, might be essential to achieve the next breakthrough in both agility and productivity [7]. This transition will pose significant new challenges for how production systems are planned and engineered to maximise the potential and to minimise the risks of the new technology introduction for businesses [8]. Throughout modern production industries such as aerospace, automotive and electronics, success will depend on the capability of companies to rapidly incorporate new production paradigms like industry 4.0. Modern production systems adapt their physical and intellectual setup to enhance manufacturing speed, sustainability as well as responsiveness to satisfy global and local customer demands [9]. To think standard automation and robotic systems have already satisfied such a demand misconstrues a manufacturing reality. A manufacturing-wide investigation of standard automation carried out in Germany indicated that a third of roughly 600 companies aim to reduce automation due to flexibility concerns for standard automation [10]. Flexibility means resilience to both, product and process changes in a manufacturing context (for example due to mass customisation or re-use of equipment). The synthesis of production paradigms from Industry 4.0, the newest developments in RAS, as well as demands from the automation community in manufacturing is the main driver for novel innovations to face the arising challenges (see Figure 1-1).

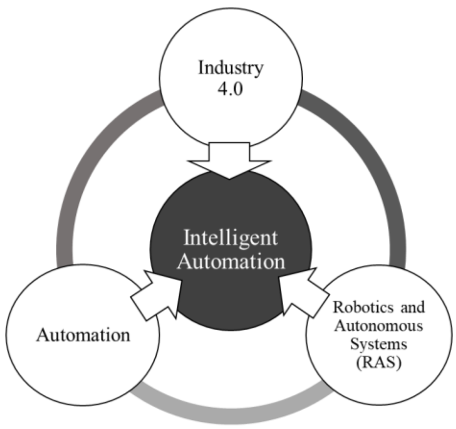


Figure 1-1: Knowledge Synthesis of Industry 4.0, Robotics and Autonomous Systems and Automation.

Intelligent Automation (IA) systems are considered as one of the potential solutions and response of the development to increase productivity and compete in a global market by resolving flexibility-related issues [11]. As automation systems strive to become smarter, faster and cheaper, they are increasingly driven towards enhanced capabilities to support more challenging and complex production processes. Enhancements of automation technology via RAS developments shift the capability beyond repetitive, dangerous and traditional tasks, such as pick and place or welding, and become more suitable for manufacturing tasks where human operations are still dominant [12]. IA embraces advanced sensing, decision-making, and actuation to form highly adaptive manufacturing automation systems that make the best use of a-priori information, as well as information, gleaned from in-process sensing, machinery condition sensing and produced part sensing [13]. The systems are designed for a variable process environment [14], [15]. More flexible systems cover those process variabilities through sensors, smart data analysis and 2D/3D vision, increasing the product quality [16]. Consequently, the smooth wider-industrial uptake of IA is a possibly crucial part of the competitiveness of future manufacturing businesses, to increase productivity and to overcome skills shortages, as well as health and safety related problems [17].

1.2 Implementation Challenges of Intelligent Automation

Frameworks supporting companies and organisations with methodologies to implement automation have been reported as key to success in the past [18]. Currently, the introduction of advanced technology, in general, has become the subject of extensive research in complementary areas like the integration of maturity metrics, cost models for technology development, manufacturing technology selection, and system integration technical risk assessment [19]–[22]. Despite significant research output in surrounding areas, the current view on the implementation of IA seems to be disconnected from the fast-paced development of the underlying manufacturing technology. Even though the implementation of IA is considered a necessity for future competitiveness, early-stage decision support to estimate automation success for the implementation of IA has not yet been provided.

Figure 1-2 presents Cooper's stage-gate diagram, which explains the decision-stage of the presented thesis [23]. The existing studies investigate the implementation of automation during later stages of the decision process (Gate 3), like robot selection [24], or costing frameworks for automation [25], [26], but only a little research has been conducted on the early stages (Gate 2). An early-stage decision is made prior to a detailed investigation and demands less effort and time from the decision-maker. Decision-makers face a high level of uncertainty driven by a low level of available information like the human task analysis for automation [27], current decision-making practices, or an update arising from new technological challenges.

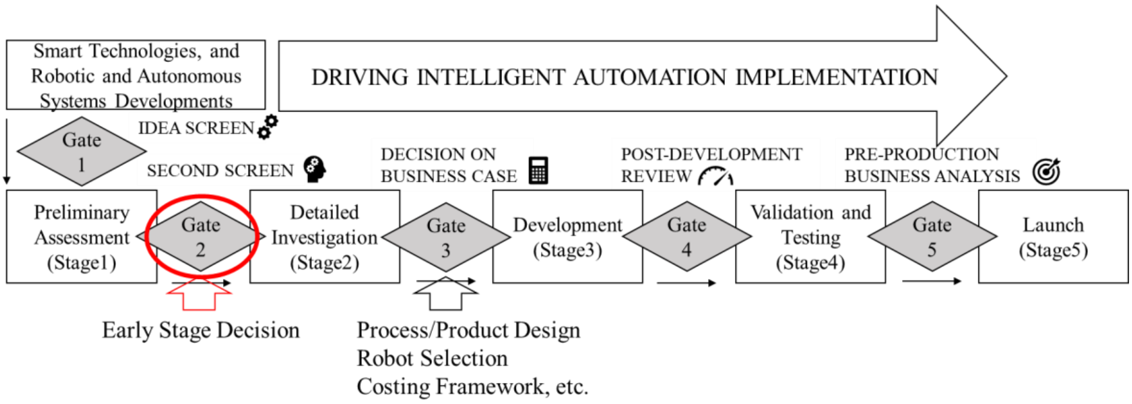


Figure 1-2: Stage-Gate Diagram for Implementing Technology derived from Cooper [23]**.**

Consequently, the question of which process to invest time and effort as the next IA project is currently challenging to answer.

The assertion is that automation decision-makers would benefit from the introduction of an early-stage decision support for implementing intelligent automation.

The study describes the development of an early-stage decision support framework for the implementation of IA. The central question of the research project is *how to identify a process for IA from an early-stage decision perspective based on limited information*. Before more detail to the research is presented, constraints to the area of application will be pointed out as part of the IA research context.

1.3 Research Context

Uncertainties for the decision-making problem for IA decision may arise from inside and outside the company. The research context is set in an endogenous research environment meaning that the arising problems are investigated taking a company-internal perspective. Two focus points are determined for the thesis. The two focus points are a human-centred approach, as well as decision-support for IA. The scope is limited to specific application areas starting with a focus on the manual process.

1.3.1 Human-Centred Research

The first basic assumption is that the conducted research will involve interaction with human operators since manual manufacturing processes are evaluated for IA.

Simultaneously, the decision support tool starts at a point in time, where the manual process information is the only obtainable information. A different view is taken for early-stage decision support from a production requirement perspective using the stakeholder position of the decision-maker/process engineer. This approach identifies process parameters to design the applicable automation solution, for example, through formal modelling of the manual work process for the application of industrial robots [28]. The problem with the approach is neglecting the manual capability to address factors like process variability and is process-parameter-centred leading to an absence of human factors. Goodrich et al. [29] stated,

"[...] that, in the absence of human factors considerations, even technologically state-of-the-art systems can be more problematic than beneficial [...]".

The statement has also been supported by other research, for example [30]–[32]. As a result, the conducted research will work on the basis that the human task of a manufacturing process is the starting point for the early-stage decision through-out the thesis. Albeit, the later tool will also demonstrate capabilities for greenfield planning.

1.3.2 Intelligent Automation

The executed research focuses on early-stage decision support for the implementation of IA in manufacturing businesses. It should be clarified beforehand, that the early-stage decision support tool might be usable for standard automation. However, the focus of the research is the support of IA. Whereas IA uses smart technologies and artificial intelligence for decision-making to adapt to process variability (flexibility), standard automation is the simple repetition of a manufacturing process without any live information that feeds information back to the manufacturing process (no flexibility). Although it may be possible to redesign the product or manufacturing process for standard automation, the assumption is that an IA solution will be the preferable choice. If a result implies the implementation of IA is within a reasonable spectrum of effort/risk, the results consider IA and not necessarily standard automation. The presented research domain defines the scope of the research questions and objectives.

1.4 Research Aim and Objectives

Based on the initial assertion, the creation of an early-stage decision support tool for the implementation of IA has been declared the overall aim. The related research question is stated below:

How to support an early-stage decision for intelligent automation?

The research aim drives different research questions. The questions are derived from a problem-solving method displayed in Figure 1-3. The figure shows the overall structure that informs the thesis according to VDI 2221 [33].

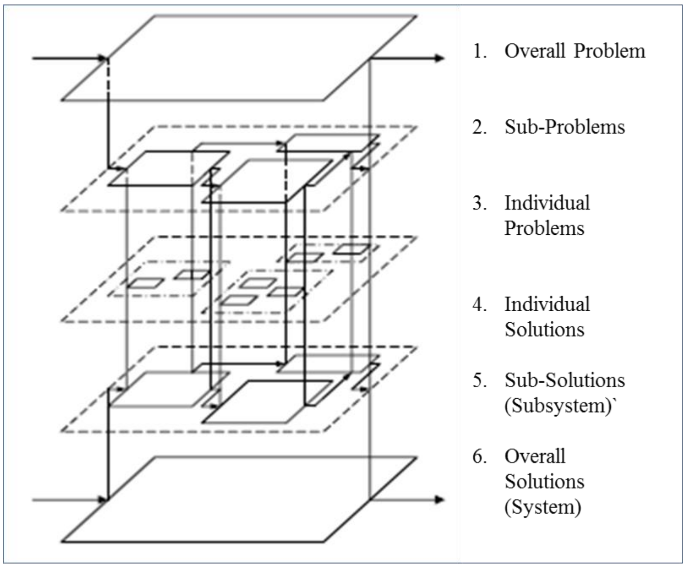


Figure 1-3: Problem decomposition and solution synthesis described in VDI 2221 [33]**.**

The research describes the structured development of an early-stage decision support framework for the implementation of IA. Using the VDI 2221 strategy, the overall problem can be disassembled into different sub-problems of research questions to be investigated for the bigger research question:

i. *Are there existing description models to represent the available information at an early- stage?*
ii. *What are the current trends that might affect early decision making for intelligent automation?*
iii. *How can the early-stage information be systematically processed towards intelligent automation decision-making?*

iv. *How to assess the manufacturing process based on limited available information for intelligent automation implementation?*
v. *How to validate the results from the framework?*

Sub-problems for the overall framework are the representation of the current situation, identification and representation of decision factors based on the current situation, decomposition and relations network between those factors, development of a decision process model, the integration of those parts into the framework and evaluation.

The development of new smart technology transforming automation into IA requires an update of critical factors related to the implementation in manufacturing. Accordingly, those factors must be identified as the decision tool should respect the most important parameters, applied to the current process to make a distinction between future manufacturing strategies.

1.5 Research Questions

The above listed sub-questions lead to individual objectives, which are are described after the questions in the following section. The first question can be seen below.

Q1: Are there existing description models to represent the available information at an early- stage?

To develop a functioning framework, a starting point for the decision framework should be determined. A logical consequence is to start with a description of important parts extracted from the manual manufacturing process. Subsequently, the objectives above are designed to achieve a description of the current manufacturing process by understanding the human task, process representation and modelling as well as the current decision-making domain. The generated knowledge allows the decision framework to be built upon. Question 1 will serve to build an interface between the current manufacturing process and the decision support framework and, thus, be informed by both, manual process and functional translation of the human task. With respect to the development of smart manufacturing technology for IA, an update of critical success factors is considered necessary.

Q2: What are the current trends that might affect early decision making for intelligent automation?

To establish the state of the art, a literature review is carried out. The review describes the previous research related to industrial automation and decision support and aims to summarize factors, which are considered important for the implementation of manufacturing automation.

In addition to that, the current changes and trends in the automation environment, a quantification of critical success factors, issues and themes related to the implementation of IA must be investigated. On the one hand, the factors might derive from the current manufacturing processes and are influenced by human tasks, the manufacturing environment, the process requirements, logistics operations, like for instance positioning and handling, as well as by the equipment used. On the other hand, they might be highly influenced by the available IA technology and, more specifically, the technology maturity level and the derived risks and costs of such an implementation.

Q3: How can the early-stage information be systematically processed towards intelligent automation decision-making?

After the existing information at an early-stage has been established, there is a need to fuse the crucial information into the decision-making process. The key components will define the decision-structure of the framework. Even though many ways of translation might lead to an acceptable solution, the framework should reduce the effort for the user and establish an approach that reduces the users' influences. The method should be repeatable and appropriate to enable early decision-making.

Q4: How to assess the manufacturing process based on limited available information for intelligent automation implementation?

Once the structure of the decision-making problem is established, a mathematical model for the decision framework is needed to determine the probability of success for IA projects, given the identified critical success factors. The approach must allow the framework to evaluate the entire system and every sub-component to decide whether the process function is suitable for IA or the process should only be partially automated.

Q5: How to validate the framework?

The last step of the research aim is that a developed tool is used and evaluated in a real-case scenario. The evaluation of the decision-support tool should be done by the investigation of the produced results and justify the generated framework. Additionally, feedback will be collected by the industrial partners about the employability of the decision-support tool. Based on the research questions, the displayed thesis structure can be logically justified.

1.6 Thesis Structure

The thesis is logically structured into nine different chapters. The first chapter (introduction chapter) has presented the context of the research and summarised domain-specific issues. The research domain has been presented and the research questions have been derived to tackle the overall research problem. The thesis is structured according to the research questions.

Chapter 2 presents a literature review of the investigated domain. The literature discussed in the chapter reflects on the research questions. First, the literature in human task decomposition for automation and process representation models are presented. The process representation model is the basis of the decision-making process. After reviewing the models, a review of the current decision-making process consequently leads to the consideration of risks and uncertainties, which are important for the understanding of the following thesis. Chapter 2 is concluded by a reflection on the reviewed literature and informs about the knowledge gap present.

The methodology chapter 3 builds upon the knowledge gap and presents the methodology and methods used to fulfil the research questions. The first part of the methodology chapter presents the higher level of the methodology structure and increases the granularity of the methodology in the second part, where the methods are presented in detail.

Chapter 4 aims to update the current perspective on IA. A survey and workshop have been created to understand the arising problems of implementing smart technologies in manufacturing businesses using a European expert database. The updated perspective finally leads to a comprehensive understanding of the research area and builds the foundation of the framing chapter. Chapter 4 is also the framing chapter and initially presents the foundation of the framing process informed by the literature review in combination with chapter 4.1. The combination enables a reflection on both, a historic view on automation and methods applied, as well as a modern view from a smart technology perspective.

The understanding leads to the development of a decision framework displayed in the first part of chapter 5. To help the decision-makers, the framework has then been realised as the logical structure for a toolbox discussed in the second part of chapter 5.

Chapter 6 is the results and validation chapter. The chapter discusses the results obtained using the created toolbox. First, the functional task abstraction is applied to a range of case studies and then validated against the expert's results using IDEF0. The decision model results from the expert elicitation are presented and evaluated.

The results and validation of chapter 6 are discussed in chapter 7. Initially, the discussion is on the functional task abstraction results in the case study context and informed by a global perspective to display differences between the current praxis and the novel clustering algorithm. The functional task abstraction both constrains and enables the decision-support using Bayesian Network (BN) models.

Chapter 8 is the final chapter of the thesis. The chapter concludes the research conducted in the thesis and reflects on contribution to knowledge. Additionally, the practical research limitations in the thesis are highlighted. Finally, several areas for future work arising from the research are pointed out.

1.7 Summary

The introduction chapter has presented an initial idea about the research topic discussed with a focus on the support of an industrial uptake of IA systems. Based on the overall research question, specific research questions have been derived. The subsequent literature review chapter addresses the first research questions as presented in section 1.4.

2 Literature Review

"To read in the future one has to turn the page in the past." – André Malraux

The following literature review represents a careful and distinct investigation of the research connected with the *decision-making for implementing automation in manufacturing businesses*. The focus of the thesis is on intelligent automation but not many publications have focused on decision-making for intelligent automation so far. However, a significant number of publications have been presented in connection to flexible and adaptive automation, as well as robotics. The presented literature review will serve as a basis for the presented research throughout the thesis. As pointed out in section 1.4, the review will serve to answer research question 1 and 2.

The literature review is divided into four different parts. As stated in the first chapter, the human task is a central starting point for early-stage decision support. Therefore, section 2.1 deals with human task decomposition for automation. The extracted human task will influence a process representation model. Section 2.2 reviews the most frequently used process representation models and methods. The basic understanding of the human task and the related representation of the task in a process model will lead to the decision-making for automation. Section 2.3 will present automation decision-making for different stages of automation decisions (early, middle) and introduce into the research accordingly. Additionally, the concept of risk assessment will be introduced. Section 2.4 will then summarise the literature findings to derive the research gaps.

2.1 Understanding the Human Task for Automation

Recent developments in the field of human task automation have highlighted the need to consider human factors for automating manual tasks [29]. *The general process of automating a human task is the creation of a process representation model derived from a manual process to design and create a technical solution.* The following figure describes the current connection of the automation process from the human task analysis towards the evaluation and assessment. Starting with the collection of information about the human task via task analysis, process representation models are used to formalise the production process. Based on the formalisation process, a solution is created derived from the production model.

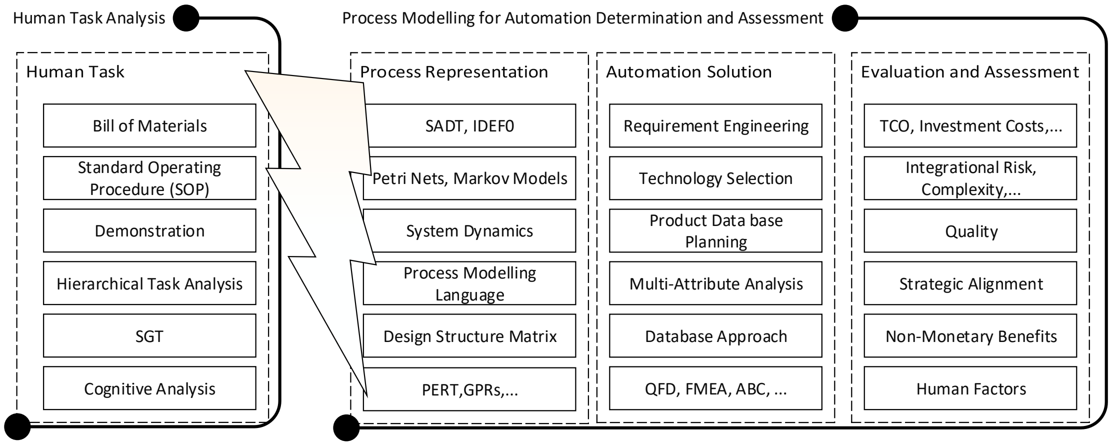


Figure 2-1: Automating a Human Task

In the displayed work, the underlying assumption suggests an automation process would follow the demonstrated stages:

i. *Understanding the Human Task*
ii. *Process Representation Method*
iii. *Mitigating from Model into Automation Design Process*
iv. *Evaluating Automation Design*

Each of the steps in the process, as well as the overall process, is conducted iteratively until a desired level of usability is attained. Based on the process, the following literature review describes a representative picture of the methods and tools used to date regarding the first three steps of the depicted process.

2.1.1 Human Task

A considerable amount of literature has been published on human factors as a fundamental part of the current manufacturing domain [34]. However, the publication's focus is wide-spread and not necessarily related to automation. The focus of automation literature reaches from applications of artificial intelligence to automatically transfer human skills via demonstration to automation systems [35] and automation component mapping [36]. Further areas are contributing towards the mental assessment and strains on humans combined with related decision-making for automation [37], to physical task analysis and decomposition. In the presented work, the focus is on physical task analysis and decomposition informing later processes of automation. The study reviews research on the current state-of-the-art of a well-established task decomposition from a physical and cognitive perspective [38]. The existing literature discusses the analysis of human tasks illustrating the importance of learning via demonstration, the Hierarchical Task Analysis (HTA), the Sub-Goal Template (SGT), the Conceptual Task Analysis (CTA), and the work-process and Program for the International Assessment of Adult Competencies (PIAAC) approach. The following table presents a short overview of the most common methods to date.

Table 2-1: Efficiency, effectiveness and empirical evidence in task analysis research derived and extended from Crystal et al. (2004).

Perspective	*Technique*	*Efficiency*	*Effectiveness*	*Evidence*
Continuous	Machine Learning	• Task Demonstration • Learning from Demo	• Works rather on action than on process level	[39]
Discrete	Hierarchical Task Analysis (HTA)	• Decompose complex tasks into subtasks • Complex activities demand extensive hierarchy construction	• Improves problem diagnosis and useful for concurrent operations • Does not account for system dynamics	[40], [41]
Discrete-Elemental	Sub-Goal Template (SGT)	• Builds upon HTA • Decompose tasks into actions using elemental building blocks	• Improves the level of detail • Irreproducible results due to lack of user expertise possible	[42]
Cognitive	Cognitive Task Analysis (CTA)	• Defines a coherent knowledge representation of the domain being studied	• Increases the understanding of cognitive aspects of the task • Captures task expertise • Fails to fully incorporate learning, contextual and historical factors	[43]
Humanist	Activity Theory	• Analyse the activity, not the task, implying a potentially great increase in scope and complexity • Requires in-depth knowledge of culture and social aspects	• Accounts for learning effects • Extents scope of technology • Requires a high level of abstraction • No disciplined set of methods • Difficult to apply systematically	[44]
Demand	Competency Assessment	• Analyse the required work skills needed for a specific task • Literacy, Numeracy and problem-solving skills analysed	• Improves understanding of the workers' skill sets needed for a specific task. • Does not consider process order	[45], [46]

More recently, problems driven by the automation-driven research community are acknowledged by a rising number in publications. Stanton and Salmon investigate the HTA and cognitive work analysis to produce a comprehensive picture of manufacturing task analysis and present a variety of different applications [43], [47]. A first approach by

Phipps et al. (2011) to extend the hierarchical task analysis adding cognitive elements of tasks and information design requirements added significant detail to the current knowledge of manufacturing task analysis [38]. Caird-Daley et al. (2013) executed a task decomposition based on an HTA to capture physical and cognitive tasks to extend the physical analysis for automation [27]. Fasth-Berglund et al. (2013) confirm the need to consider cognitive as well as a physical task as part of the automation strategies for reconfigurable and sustainable systems [48]. Based on an HTA analysis, Everitt et al. (2015) aimed to tackle the goal of a “robust, formal skill capture for assessing the feasibility and implementation of intelligent automation” [49]. An invented dual methodology approach (DMA) combining the existing HTA methodology with a classification system aims to further increase the understanding of what an automated solution might look like [49]. Purposefully, the analysis with human perception senses was extended, and a specific task classification, as well as a description of the decisions, made. Applications of an HTA based on Caird-Daley et al. demonstrate a knowledge gap, where the transition from an extended HTA process towards automation system design is bypassed [50]. Latest research publications demonstrate the transfer of human tasks into automated tasks. And yet, a transfer has not been achieved without substantial effort for the user in combination with a limited area of applications requiring detailed domain knowledge. A more universal approach might be desired to comprehend human task information systematically [51]–[53].

2.1.2 Task Complexity

The following chapter introduces the task complexity research to date. The research area is influenced by the task complexity arising from human perception, the cognitive processing of information, and the physical task complexity.

A. Perception Complexity

Koenig et al describe task complexity factors for task aiding in a visual evaluation context. His main findings are a relationship between speed and accuracy (negative), as well as a relationship between performance and task complexity (negative) [54]. Parallel to Koenig, other researchers investigated the influence of a paced task on the complexity, especially related to decision-making and perception [55]. Tetteh et al. reveal relationships between the way of visual perception and speed as a factor for task complexity in a visual inspection background. The findings imply that the most effective way is to search for defects in a reading-like manner (familiar way) and with a medium pace for defect detection [56], [57]. The last recent investigation describes a master-slave teleoperation setup, in which the robot is controlled by a human operator. In the present context, a task complexity metric has been developed and compared to the Task Load Index developed by the National Aeronautics and Space Administration (NASA-TLX) framework. The NASA-TLX framework is a simple workload assessment form highly adopted by the industry. The study also shows elements of cognitive complexity as perception complexity is reduced to mitigate the effects on the cognitive complexity [58]. From an automation perspective, the studies introduce a humanist perspective on the perception complexity. Despite the unremitting research efforts, investigations must determine how human perception complexities specifically translate into automation perception complexities.

B. Cognitive Complexity

The first paper demonstrates a measurement and design to counter information complexity in a nuclear power plant environment. The results suggest that active involvement and logical relationship between information provided leads to a better performance of the operator. Simultaneously, the result confirms the influencing factors of Nielsen (2005) for cognitive complexity to be valid [59]. Nielsen suggests 10 principles including system status visibility, a close-to-reality representation of the system, user control and freedom, consistency, standards, error prevention, recognition vs. recall, usability, aesthetic and minimalism in design. In the next publication, the numeric relationship between mental demand and task complexity in highly interdependent tasks was investigated [60]. Additionally, dissimilar task criticalities were provided for different tasks. The result was that a highly critical task leads to a negative effect on the mental demand. Further interview indicated an effect in which the individuum reduces the task assignment search space by giving higher priority to critical tasks leading to fewer alternative solutions for remaining tasks. The findings support the activity theory, in which the hypothesis is made that an active worker means a reduction of process errors [61]. The next findings demonstrate a clear dependency between the performance of operators related to the information complexity. The study found that information complexity was influenced by the way the information was provided. A central aspect of the study was the visual design of the provided information [62]. In their conducted research, Lyell et al point out that low, as well as high cognitive workload, lead to errors. Therefore, the impact on task complexity is also dependent on the workload allocated to a specific task. Therefore, an over-dimensioning of cognitive support systems may lead to an increase in errors causing a reduction of the cognitive workload. A reduction of task complexity means the right level of cognitive load to keep the operator active, but avoid time pressure or too complex information [63]. A generic problem with the research area is the focus on a reduction of cognitive workload rather than an attempt to inform about the automation complexity. On a critical note, more contributions are needed to understand the implications of cognitive complexity on the programming side of automation and, in combination with the perception complexity, the sensor network design.

C. Physical Task Complexity

The physical task complexity focuses on a humanist perspective rather than on identifying a connection between physical task complexity and automation complexity. The first recent study found, as side-effects, a relation between task complexity and physical strain [64]. The study has proven a weak link between physical strain and the mental side of task complexity. The results are in contrast to other studies in dissimilar fields, like sports, which reported that an increase in physical strain leads to errors in decision-making [65]. A possible explanation is the lack of operator exposure to highly intensive tasks over a long period of time, in contrast to an athlete. Another contribution by Alkan assesses the task complexity of manual assembly operations using pre-determined motion time systems [66]. The aim is to predict the task complexity for the human operator. Even though, the contributions present information required for the assessment of human task complexity, an implication of the effects on automation is still required.

D. Complexity Analysis and Impact

The last part of the task complexity investigation deals with the analysis and impact of complexity. In the first study, the generated neural network is used to make a statement about the task complexity based on the neural structure design of the created controller decision network [67]. Circuit Task Complexity and Robot Task Complexity are calculated immersively to determine a new metric for measuring tasks involving robots, called Task Fidelity. The results suggest tasks with an optimal Task Fidelity degree. However, the application is related to combine different stages of multi-objective applications as in a transition complexity for mobile robot applications [68]. Mat et al focus on problems of motivation and job satisfaction related to task complexity. Results reveal unskilled workers prefer group working on complex tasks whereas skilled workers prefer to work alone on a complex task. Retrospectively, the underlying dependency might be used to identify high complex tasks due to the number of workers allocated [69]. Harbers et al recently pointed out that autonomy can be related to the complexity of a system [70]. However, if the task is not complex, the related system would be called automated rather than autonomous. Therefore, it is argued from a perspective, where the term autonomy is related to systems that execute a self-directional, machine-learning, or emergent action as a response to a complex task. The participants confirmed the theory. If a task was found to be simple, the system was either rated highly or hardly autonomous, whereas for high complex tasks a consensus for the system to react much more autonomous than usually was reported. Meaning an increasing task complexity asks for a system that acts progressively autonomous. From the perspective of a contribution to complexity, an overview was created by Liu et al. (2012), which combines different factors influencing the task complexity of a manufacturing task. The findings correlated to a high extent to findings published in the presented publication with co-authorship of Sanchez-Salas. However, those factors have not been part of the automation decision domain to date. Reflecting on task complexity overall, additional research is needed to understand the implications of task complexity on the automation and, in combination with the perception complexity, the sensor network design. However, research implicates that an increasing task complexity asks for a system that acts more autonomously.

Table 2-2. Parameters to describe variability from literature by Sanchez-Salas[1]

Variability parameters important in task complexity	*Papers*
Number of elements	[71]–[73],
Number of information cues, information load	[74]–[77]
Number of products/outcomes	[78], [79]
Variety/diversity of elements	[80], [81]
Presentation heterogeneity	[74], [77], [82]–[85]
Uncertainty	[71], [72], [74], [77], [81], [83], [86]
Connectivity/relationship	[74], [76], [81]
Number of paths/solutions	[87]–[89]
Number of alternatives	[77], [90]–[92]
Number of operations/sub-tasks/acts	[76], [81], [93]–[97]
Structure/specification/clarity	[76], [98]
Repetitiveness/non-routinely	[82], [96], [97], [99], [100]
Concurrency	[89], [96], [97], [101]–[104]
Time pressure	[97], [101], [105], [106]
Format/mismatch/inconsistency/compatibility	[97], [101], [104]
Difficulty	[74], [97], [107]–[109]
Cognitive demand	[74], [97], [107]–[109]
Physical demand	[78], [79]

By implication, the future of automation will require more autonomous systems due to the increasing complexity of remaining manual tasks. The following part of the literature will present the current process representation area before the central findings in the automation decision-making domain are established.

2.2 Process Representation Methods

A key aspect of modern research on production is the development of process representation models. Process representation models are used in various ways. A model is an artefact systematically representing the ideal inner relations and functions of reality in an abstract way to reduce the complexity. An extensive literature review to analyse the current landscape of existing production description models has been executed. The following table is a summary of the most commonly used process representation methods to date.

[1] The table was created by Sanchez-Salas as part of the collaborative paper.

Table 2-3: Description of Process Representation Models.

Tool	*Abb.*	*Description*	*Inventor*
Activity Networks (Flowcharts, PERT)	-	Graphical Representation of Task Dependencies and Times	Kelley, Walker
Activity/Phase Overlapping	-	Overlapping Activities Based on Sensitivity and Evolution	Krishnan, Eppinger, Whitney
Business Process Modelling	*BPM*	Event-Driven, Discrete Modelling of Business Processes	White
Control Theory Models	*CTM*	Using the Laplace (Z-) Transformation to Design Process Control	Ragazzini
Design Structure Matrix	*DSM*	Graphical Dependency Matrix for Complex System Design (Applied to Complex Tasks)	Steward
Generalised Precedence Relation	*GPR*	The Model Describes Time Constraints Between Activities.	Elmaghraby
Goals, Operators, Methods, Selection Rules	*GOMS*	Model to Represent Human-Computer Interaction via Goals, Operators, Methods and Selection Rules	Card
Graphical Evaluation and Review Technique	*GERT*	Describes a Probability-Time Relationship of a Processes Through Stochastic Networks.	Pritsker
HAMSTERS	-		Martinie
Input-Process-Output, Entry-Task-Validation-Exit	*IPO, ETVX*	Model Defining Process via Entry Criteria, Tasks, Validations and Exit Criteria	Radice
Markov Models	*MM*	Stochastic Model Describing Randomly Changing Systems Trough State Transitions.	Markov
Petri Nets	-	Model of Discrete and Distributed Systems to Describe Transition Processes	Petri
Phase/Stage-Based Modells	-		Boehm
Process Grammars/ Languages	*UML, SysML, YAWL*	Models Describing the Process/Workflow with a Standardized Language	-
Queuing Theory	-	Describes a Probability-Time Relationship of a Process Through Stochastics.	Erlang
Signposting	-	Activities with Input Requirements and Output Capabilities Based on Information Confidence	Clarkson, Hamilton
Structured Analysis and Design Technique, Integrated Definition 0	*SADT, IDEF0*	Graphical Method to Describe Inputs, Outputs, Mechanisms and Control for Functional Process Representation	Ross
System Dynamics	-	Modelling Non-Linear Systems Using Feedback Loops, Stocks, Time Delays, Flows, and Functions	Forrester
Task (-Related) Knowledge Structure	*TKS*	Model to Represent Task-Knowledge	Johnson
Value Stream Mapping	*VSM*	Mapping Model to Analyze Current and Future States of Parts, and Products in the Supply Chain	Rother and Shook

The following research on existing process representation models in manufacturing is indistinctly divided into four different categories related to the most recent applications of those models. The four categories are production layout, production information, production schedule, and production optimisation.

- *Production Layout* here represents a category for process representation tools capturing the setup of the production system. Models describe hereby the dimension of the system including skills and capabilities as well as the used components of the production system. Models in this respect are used to dimension the production system.
- *Production Information* means the related model is primarily used to provide information about the manufacturing system. Applications of these forms display requirements of the production process. The process models can be informed about various aspects such as the representation of knowledge, dependencies between tasks, or the workflow and value stream within the production system.
- *Production Scheduling* describes a category used for tools modelling the schedule of a production system. The representations are used to provide information about the time structure of the production process. The tools can represent the time sequence of processes, the overlap within the production, as well as the transition from one production moment to another. The gained results can later be fed into optimisation tools or inform the design of the production system.
- *Production Optimisation* methods are used to improve the current situation by using a model that twins a production reality. An improvement of the situation can be achieved by predicting a future outcome, identifying bottlenecks, or optimising the service at production stations.

The outcomes of the conducted analysis can be found in the following table (see Table 2-4). Adding additional information needed to understand the idea behind the thesis, another column was provided indicating whether the model required the input of a task analysis.

Table 2-4: Process Description Models

Process Representation Model	*Abbrev.*	*Task Analysis Required*	*Production Layout*	*Production Information*	*Production Schedule*	*Production Optimisation*
Control Theory Models	CTM [110]	No				
Goals, Operators, Methods, Selection	GOMS	Yes/No				
HAMSTERS	HAMSTERS	No				
Task (-Related) Knowledge Structure	TKS [111]	Yes/No				
Signposting	SP [112]	No				
Activity Networks	(Flowcharts, PERT) [113]	No				
Activity/Phase Overlapping	AO, PO [114]	No				
Generalised Precedence Relation	GPR [115]	No				
Graphical Evaluation and Review Technique	GERT [116]	No				
Petri Nets	PN [117]	No				
Markov Models	MM [118]	No				
System Dynamics	SD [119]	No				
Design Structure Matrix	DSM [120]	Yes				
Structured Analysis and Design Technique	SADT, IDEF0 [121]	Yes				
Business Process Modelling	BPM [122]	Yes/No				
Input-Process-Output, Entry-Task-Validation-Exit	IPO, ETVX [120]	Yes/No				
Process Grammars/ Languages	UML,SysML, YAWL,..[123]	Yes/No				
Value Stream Mapping	VSM	No				
Queuing Theory		No				
RESEARCH AIM	ESDS	Yes				

The presented results in Table 2-4 indicate a lack of connection between manual task analysis and various production description models. In most of the cases, the models do not require an analysis of the manual task. The transition of human tasks to a process model description might cause a loss of critical process information. The proposed work aims to transfer the human task directly into a production information model to elude the production layout. Conversion of human tasks into the design of a manufacturing production system would add significant value to the current production environment.

2.3 Decision-Making for Automation

This section presents the previous work considering the implementation of intelligent automation in manufacturing businesses to date. The review is logically divided into four different categories. The categories are namely *critical success factors and automation strategy*, *product and process design techniques*, *technology selection*, as well as the *early-stage decision support*. The following sections will present those categories chronologically as displayed in Figure 2-2 before starting with the strategic perspective.

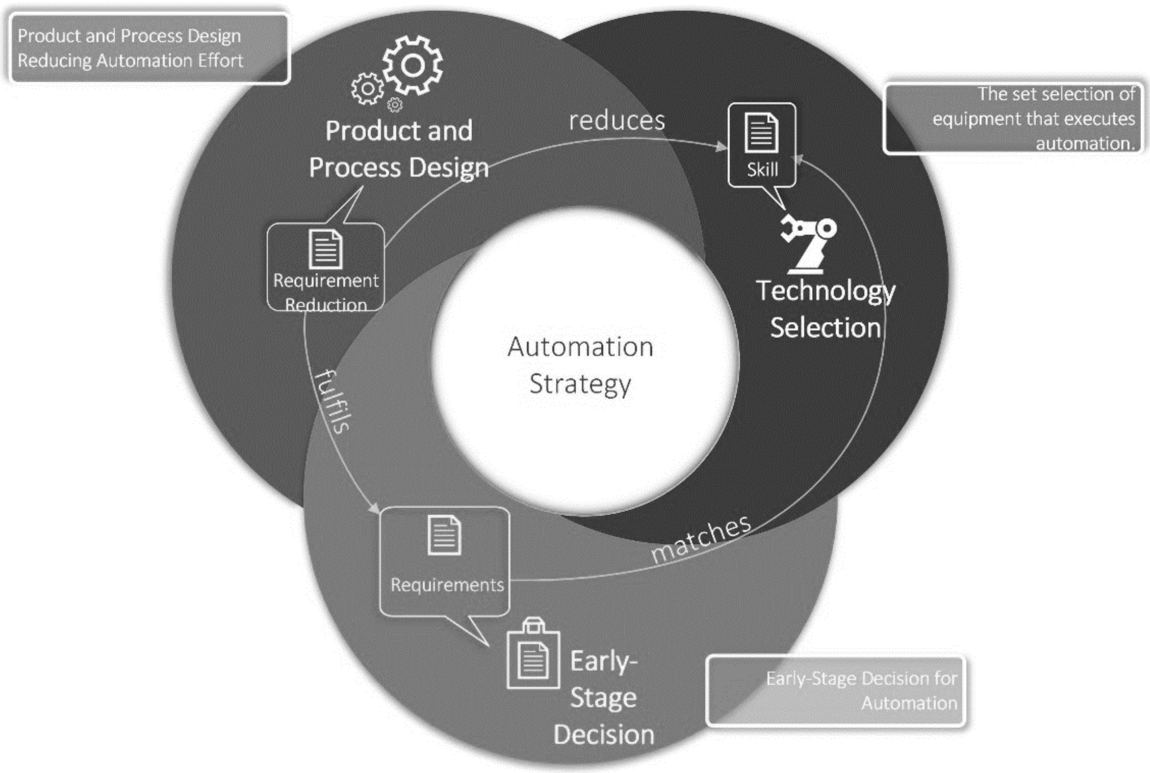


Figure 2-2: Literature Review – Overview.

2.3.1 Critical Success Factors and Automation Strategy

The discussion of automation and computer integrated manufacturing strategies and implementation factors started a considerable amount of time ago and was mainly investigated before the millennium. One of the earliest strategic discussions about automation in manufacturing was presented by Merchant in 1983. The central point was the potential for automation in the metalworking industry [124]. Other research investigated different case studies to identify the steps required for successfully implementing automation. The perspective, however, was a high-level investigation not offering specific information about which process to automate from an early-stage perspective [18]. The discussion of the nature and potential of computer integrated manufacturing systems came up and extended the knowledge of computer-integrated manufacturing systems and their potential further [125]. Nagel et al. [126] identified the need for new tool development for future manufacturing. Meredith conceptually recognised and discussed critical success factors for an automation project [127], added a discussion to the research community how to implement automation in a manufacturing environment by acknowledging the critical success factors identified [128], and compared theory and praxis of the automation implementation by highlighting the differences [129]. Meredith contributed to the research environment from a generic/exogenous perspective and many of his findings have been confirmed later by industrial case studies (for example management involvement). Around the same time, research acknowledged first issues related to computer-integrated manufacturing and developed a high-level methodology of how to implement CIM in manufacturing [130]. In the further course of the CIM literature, a new terminology came up called automation and papers occurred introducing decision support for automation implementation. The starting point is a Japanese perspective [131] and the further identification of critical success factors [132]. Naik et al. [133] introduced a 3-layered decision support tool for automation covering a strategic, operational and financial perspective. The decision support presented in the paper, however, is found to be basic and lacks the consideration of process information (like variability). The description of attributes as requirements for a suitable reference architecture used for automatic optical inspection systems are demonstrated but are devoted to the specific application [134]. Attaran points out factors for the implementation of CIM again but the results lack specific solutions on how to consider those factors and support the decision maker [135] similar to Xue et al. [136]. Papers from other authors present case studies about lessons learned from the automation implementation in Spain [137] as well as the adoption of advanced manufacturing technologies [138]. The results from the case studies are found to be very detailed but lack decision support. Building upon previous research, the investigation shifted from a high-level approach to the investigation of human factors related to the implementation of advanced manufacturing technology, as those factors were reportedly pointed out as issues by previous studies contributing to a better understanding of advanced manufacturing technology implementation [139]. More recently, the previous identification of CSFs and automation strategies were extended by the aspect of sustainability [140] and process variability [141]. A current investigation of critical success factors identified in a wide range of automation topics with the help of a text mining tool. A disadvantage of the investigation is, however, that the tool could only identify already discovered factors [142].

Overall, an investigation of critical success factors and automation strategy domain shows that the critical success factors seem to be outdated and there is a lack of solutions to select automation projects. The research focus seems to be on factors, which ease the implementation of automation for an already selected production process. Another perspective for the implementation of automation support is connected to product and process design techniques.

2.3.2 Product and Process Design Techniques

Before the next section introduces, which technologies should be selected (Technology Selection) to perform the specific tasks, product and process design techniques aim to reduce the automation effort. The overall perspective on automation is consequently related to different product and process design techniques to accelerate the implementation of automation. Either the design is reduced to standardized features or generally reduced in its complexity, or the process is based on the product design.

Mayer et al. use an object-based automation approach for automation based on systematic process planning via CAD product data [143]. Coming from a slightly different perspective, other research has identified the possibilities of a multi-attribute analysis of basic factors, which can be used in the design stage of an automation decision process [144]. Database approaches to add information for factory design were developed to integrate different views of a manufacturing enterprise [145]. Saleh et al. present a hierarchical attribute structure influencing the decision-making process for advanced manufacturing technology [146]. The research is directed towards the design of the automation system which is related to capital decisions considering data of later automation decision stages. Similar to Meyer, Sanders et al. introduce an expert system enabling the development and evaluation of a production system based on CAD-data [147]. Cost and quality aspects of manufacturing are introduced using QFD, FMEA and ABC for process selection. The approach is presented as a possible solution during the design stage of automation [148]. Other research takes on recent advantages of composite structural product data to improve the design, analysis and manufacturing productivity by implementing an international standard. Rather than supporting an automation decision, the research concentrates on design for automation [149]. Valente et al. present an approach that increases the reconfigurability of control software aiming at the design stage of an automation project [150]. Latest developments are based on machine communication techniques for M2M (machine to machine) communication. The interaction aims at the system design stage of the automation process [151].

Another perspective on automation design is the level of automation. Automation design decisions are considered extremely important as disproportionate levels of automation may be detrimental to operator performance [152], [153]. Consequently, finding the right Level of Automation (LoA) to apply has become critical. Manufacturing processes are either manual or semi-automatic, combining automated and manual tasks. The intricacy of manufacturing systems increases due to current trends in customised products and rises in product complexity [154], including tighter tolerances. Thus, human skill is an important asset in the manufacturing process, and as such, skilled operators and automated systems are essential for achieving flexible and productive manufacturing environments. Finding the right LoA to apply has become critical. According to Williams and Li (1999), automation can be divided into mechanisation and computerisation. Most tasks within manufacturing processes present a mix of both, mechanisation and computerisation. Taking into consideration the two aspects, automation in manufacturing should be considered as an interaction between physical tasks and cognitive tasks. Frohm et al. (2008) proposed a classification composed of seven different levels, considering two separate scales associated with the two types of level of automation, physical and cognitive as seen in Table 2-5. The classification takes into consideration both physical and cognitive actions separately. In contrast to other models, the present model organises actions into two types: mechanisation (physical) as well as information and control (cognitive) allowing the assessment of an independent LoA for both types of actions. The scale will be applied later to suggest LoA for tasks.

Table 2-5. Classification of the level of automation according to Frohm et al [155]

LoA	*Mechanisation*	*Information and control*
1.	Totally manual. No tools are used, only the users own muscle power. e.g. The users own muscle power	Totally manual. The user creates his/her own understanding of the situation and develops his/her course of action based on his/her earlier experience and knowledge. e.g. The users earlier experience and knowledge
2	Static hand tool. Manual work with the support of a static tool. e.g. Screwdriver	Decision giving. The user gets information on what to do or proposal on how the task can be achieved. e.g. Work order
3	Flexible hand tool. Manual work with the support of a flexible tool. e.g. Adjustable spanner	Teaching. The user gets instruction on how the task can be achieved. e.g. Checklists, manuals
4	Automated hand tool. Manual work with the support of an automated tool. e.g. Hydraulic Screwdriver	Questioning. The technology questions the execution if the execution deviates from what the technology considers being suitable. e.g. Verification before action
5	Static machine/workstation. Automatic work by a machine that is designed for a specific task. e.g. Lathe	Supervision. The technology calls for the users' attention, and direct it to the present task. e.g. Alarms
6	Flexible machine/workstation. Automatic work by a machine that can be reconfigured for different tasks. e.g. CNC-machine	Intervene. The technology takes over and corrects the action if the executions deviate from what the technology consider being suitable. e.g. Thermostat
7	Totally automatic. Totally automatic work, the machine solves all deviations or problems by itself. e.g. Autonomous systems	Totally automatic. All information and control are handled by technology. The user is never involved. e.g. Autonomous systems

However, as the level of automation will be applied to a task level, a clear distinction between physical and cognitive actions cannot always be made. The approach is similar to others throughout the current literature, where most authors apply LoA to tasks without any distinction between physical and cognitive tasks [152], [156]–[160]. If the lowest level of automation is completely manual and the highest level of automation is fully automated, studies have demonstrated intermediate LoA to entail a superior performance [158], [161] and decrease the operators' workload [162]. Being dependent on automation makes operators highly vulnerable to situations of system crashes, and the degree of their reliance will increase the magnitude of the impact proportionally [163].

As a summary of the product and process design techniques, the automation implementation engages in the design stage of the process and products to reduce the integrational effort. For early-stage decision support, the papers either lack focus (design stage instead of early-stage) or presents work based on unavailable data for early-stage automation decision. However, the consideration of different levels of automation for the design stage should be kept as an idea for the decision support tool. Some tasks might be fully automatable whereas other tasks might require human-robot interaction in confined workspaces. Based on an optimised design of process and product for automation, the appropriate technology should be selected.

2.3.3 Technology Selection

Technology selection is one of the most important parts of automation decision-making enabling the selection of an appropriate automation tool based on company requirements. Therefore, a substantial amount of research has been produced to date. The following chapter aims to present a chronological development of technology selection research related to the implementation of automation.

The first presented work is a comparison of different robots based on subjective and objective (mainly costing) factors for the technology selection process. The tool requires a lot of knowledge about the actual design of the process [164]. A different method to select the appropriate technology is the development of a rule-based expert-system [165]. Those methods were extended by an approach evaluating subjective and objective decision criteria using an Analytic Hierarchical Process (AHP) as a structured technique to organise complex decisions [166]. Following on the statistical approach, other techniques followed creating multi-attribute comparisons [167], fuzzy multi-criteria decision methods [168] and Data Envelopment Analysis (DEA) methods [169]. Karsak extends the DEA [170] and average weighting [171] methods by introducing fuzzy criteria values. New statistical methods enter the research domain with a fuzzy 'Technique for Order of Preference by Similarity to Ideal Solution' (TOPSIS) robot selection via a similarity-to-ideal-solution analysis [172] and decision matrix for attribute-based specification comparison and selection [173]. Kapoor et al extend the AHP process by using fuzzy methods for robot selection [174]. The research area is extended by a more financially focused perspective on technology selection by applying a Total Cost of Ownership (TCO) approach for system comparison [175]. Similar to Chu et al. a fuzzy TOPSIS method appears for robotic systems evaluation considering the hierarchical structure of the technology selection problem [176]. A new approach is a connection between fuzzy regression and AHP methods with a Quality Function Deployment (QFD) method for technology selection [177], [178]. Other methods like VIKOR and ELECTRE including later extensions [179], [180] as well as the construction of weighted sum matrices were developed to rank and evaluate industrial robots [181]. In addition to those multi-criteria methods, other mathematical programming methods are introduced that use specific goal functions for the technology selection. Examples can be found in Kentli et al. [182] in form of distance measurements based on a satisfaction function or later in Ordoobadi et al. [183] using a Taguchi loss function to optimise applications within a supply chain. Different from the existing methods for industrial robot/ technology selection, fuzzy diagraph methods [184], fuzzy decision tree methods [185] have additionally been presented to solve technology selection problems. More recently, the research area is directed towards the optimisation of already used multi-criteria decision-making applications, like weighted factors [186] and weighted decision matrix methods [187], fuzzy-based regression models for robot selection [188], modification of pure fuzzy TOPSIS [189] or combined with VIKOR via Brown-Gibson index calculation [190] and DEA methods picking the closest to ideal solution [191]. The development of technology selection has diverted from the statistical or mathematical perspective and decision-making framework for technology selections are introduced as well as tested for industrial case studies. However, the decision framework aims to connect technology selection and the supply chain, yet is not focusing on the implementation of automation [21]. Other work introduces different factors for technology selection (risk, strategy, finance) to determine a more suitable advanced technology selection [192]. A better overview and description of the specific area can be found in a detailed literature review by Koulouriotis [193] and Ketipi [194] (Part A and Part B).

A closer look at the specific literature related to technology selection points out a few problems related to the research questions. The investigated papers acquainted with different statistical and design approaches to reduce uncertainty and combine objective and subjective criteria rather than on the implementation of automation in manufacturing businesses. The technology selection stage requires more information than the information available for early-stage decision. In addition to that, a lack of new methods is discovered to support decision-making (for example Bayesian Belief Networks).

2.3.4 Early-Stage Decision-Making

Early-Stage Decision-Making might be one of the most difficult areas of automation decisions. Reasons are the high uncertainty and high risk involved in an early-stage decision (section 2.3.5). The problem is generally approached from two different directions or a hybrid version of both. The first approach is to take a cost estimation perspective. In this way, the aim is to get a cost prediction or determine a cost score based on cost influencing factors reducing related uncertainties. The second approach deals with an evaluation of the related risk. The first paper, however, describes a collaboration methodology of experts to improve the product design for manufacturing purposes [195]. The approach aims to reduce the automation effort due to product adjustments for automation but is not directed to assess a process for automation [195]. A risk approach is presented by Almannai et al. mixing a QFD and FMEA method to address different categories of decision factors [196]. Despite the carefully modelled work, the categories are generic factors rather than process-driven parameters [196]. A cost estimation technique to forecast advanced manufacturing technology development and hardware costs is presented by Jones et al. The presented research bases the costing studies on high-uncertainty but the related research is supported by a limited amount of case studies [20], [197]. An extension of the studies on multiple case studies might identify the cost structure of development project costs. An additional investigation examines the decision on the level of automation based on current approaches. The author criticises the results and states that the results lack a justification of the outcome. The presented work by Salmi et al. points out problems with the existing approaches and discusses the findings [198]. The last reviewed paper uses the widely adapted Technology-Readiness-Level (TRL) to approximate the system risk [199]. The TRL level reduces with an increase in system complexity. More components mean higher complexity and higher complexity means lower TRL level. The reason is that an increase in components reduces the readiness level of a system significantly as problems appear from an implementation of multiple components. The risk related to a system increases through novel implementation issues, which affect the technology readiness level. Even though the presented concept in the context seems reasonable, an application of the concept might difficult as the design information to assess a component with regards to the TRL level is missing. At the same time, the assessment of an unwanted outcome might provide necessary aid for decision-makers to decide on which process to automate using a hybrid approach of risk- and cost-assessment. Due to the time constraints of the project, the focus is on the risk assessment perspective during the following thesis as design information at an early-stage is missing.

2.3.5 Risk Assessment

Risk assessment techniques are widely used in cases where the determination of costs is difficult as the design of the product, service or project is highly uncertain. The evaluation/feasibility of intelligent automation in manufacturing businesses should be understood as such a problem with the objective to automate the manual production process. The variability of decision factors, especially at early stages of such decision points is widely recognised as uncertain and, therefore, may require the assessment of related risks. The following review part moderates the reader's uncertainty about the risk term and related concepts used throughout the dissertation. The review begins the clarification by introducing the concept of uncertainty.

A. Uncertainty

Uncertainty has been frequently used throughout research in related domains like supply chain flexibility [200], investment uncertainty [201] and forecasting uncertainty [202] as well as production planning uncertainty [203] and is an essential building block of a modern manufacturing management understanding. *Uncertainty* in the following research is defined as *the lack of knowledge subject to time about the involved variables, states and their outcome characterising a physical system*. Uncertainty is a function subjective to the evaluator, mitigated by determination of identified/ measured/ estimated (by experts) variables and states over time.

For the implementation of intelligent automation, the physical parameters of the later system are uncertain at an early stage. The uncertainty will reduce over the given project time by increasing information (system design → technology selection → simulation → optimisation). At the earliest stage of an automation decision, however, the only process specific information originates from the manual task and technical data. Generally, two different factors must be considered when dealing with uncertainties. The projection of costs and risks involved must be addressed. In this thesis, an epistemological approach is adopted based on objective uncertainty (see Figure 2-3). This is a response to the uncertainty of the automation feasibility with a knowledge-guided decision process based on the available process information and expert knowledge. Another possible approach is the creation of rational relationships to cover risks and produce quasi-rational decisions [204].

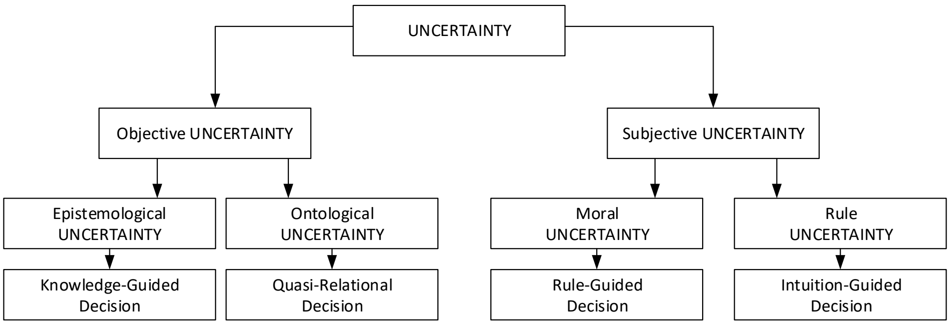


Figure 2-3: The taxonomy of uncertainties and decisions [204]**.**

Uncertainty is a degree to which a state, parameter or outcome is believed to be true, whereas a probability is a numerical description of a likelihood. The impact of the outlined difference will be visible in Chapter 5 dealing with the creation of a Bayesian Belief Network. According to Kreye et al. [205], uncertainty can be classified using five layers. The five layers are nature, cause, level, manifestation and expression. The nature of uncertainty describes inherent variability or a general lack of knowledge. The cause reasons for the source of the present uncertainty and the level present the severity. Manifestation describes the point of occurrence and expression describes how uncertainty can be communicated (measurable or immeasurable) [205].

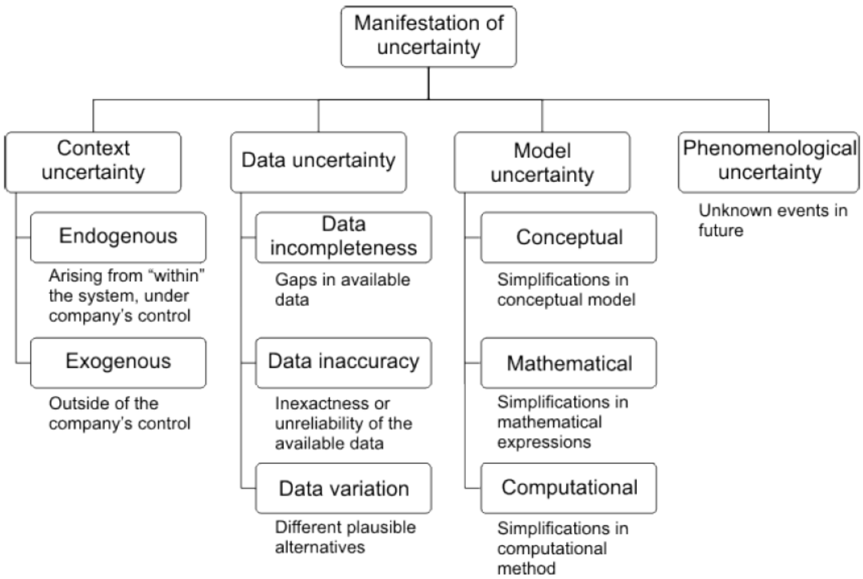


Figure 2-4: Proposed classification for the manifestation of uncertainty by Kreye [205]**.**

Current approaches as a response to various types of uncertainties in the manufacturing domain are presented in Table 2-6. The table is based on a classification provided by Mula et al. [203], investigating models for production planning under uncertainty.

Table 2-6: Uncertainty Models Present in Manufacturing with Description

Uncertainty Models	*Description*
Conceptual Models	
Yield Factors	Factor of Usage Quantity Survival Percentage for Incorporation into Final Assembly
Safety Stocks	Additional Quantify Hold to Mitigate Out-of-Stock-Risk
Safety Lead Times	Additional Time Hold to Mitigate Out-of-Lead-Time-Risk
Hedging	Loss Compensation via Compensating Transactions
Overplanning	Increase Production Schedule Orders to Satisfy Demand Fluctuation
Line Requirements Planning	Demand Information Transfer from Customer to MRP System of Production
Flexibility	Functional Modelling of Flexibility Based on Varying Demand Quantities and Times
Artificial Intelligence-Based Models	
Clustering	Extraction of Dataset Pattern Through Data Similarities
Expert Systems	Database-Driven Approach to Expert-Knowledge-Based Decision-Making
Reinforcement Learning	Objective Function/Reward-Driven Learning Approach Based on Trial and Error
Fuzzy Set Theory	Set Membership Likelihood Description for Uncertainties
Fuzzy Logic	Reality Description Membership Likelihood Translated to A Multi-Layered Reality Membership Description
Neural Network	Computational Approach akin to a Human Brain Using a Linear and Non-Linear Divide and Conquer Strategy to Create an Artificial Description of a Large Dataset.
Genetic Algorithms	Search Heuristics reflecting the Natural Selection Theory.
Multi-Agent Systems	Defined Behaviour and Interaction of Multiple Agents Solving Problems Beyond the Individual Capacity of a Monolithic System
Analytical Models	
Hierarchy Process	Structured Technique for Organising and Analysing Complex Decisions
Mathematical Programming: (LP, MILP, NLP, DP, MOP)	Optimal Allocation of Limited Resources Among Competing Activities under a Set of from the Subject Arising Constraints
Stochastic Programming	Framework for Modelling Optimisation Problems Containing Parameter Uncertainties
Deterministic Approximation	Using probabilistic distributions of two approximate deterministic values for uncertain parameters affected by multiple distributions
Markov Decision Process	Discrete Stochastic Decision Process for Situational Decision Making
Simulation Models	
Monte Carlo Techniques	Repeated Random Sampling with a Specific Underlying Distribution for Variables
Probability Distribution	Occurrence Analysis to Establish a Parameter Distribution
Heuristic Methods	Practical Method for Receiving an Immediate Approximation of an Uncertain Parameter
Network Modelling	Reducing Uncertainty by Creating a Simplified Relationship Database Model for an Uncertain Reality
Queuing Theory	Describes a probability-time relationship of a process through stochastics.

The reduction of uncertainty by the presented methods can be implemented to determine and assess the implied risk.

B. Risk Assessment and Mitigation Methods for Early-Stages

In similar research areas, e.g. civil engineering, a risk is defined as *exposure to the consequences of uncertainty, and it's consequence considered an undesirable outcome that can be identified and quantified through impact and likelihood* [206].

From a manufacturing businesses' perspective, the risk may show from a monetary perspective in a lower income than anticipated or higher expenses than projected. However, to reduce the uncertainty and the related exposure to such a risk, the perspective will later be updated to create the current perspective described in Chapter 4. Based on the new perspective, the uncertainty may be reduced further by using the methods previously described.

So far, the reviewed decision-making process indicates a lack of guidance from an early-stage perspective. From a risk modelling perspective, several methods for the determination of risks using either expert-knowledge, historical data or both for an evaluation of the occurring risk have been developed. The following paragraphs will present a selection of common risk analysis and assessment methods to date for early-stage risk assessment. Identifying failures to make design recommendations mitigating the predominant failure modes has been addressed by several methods in the literature [207]. Failure Mode and Effect Analysis (FMEA) based models use a failure mode's likelihood of occurrence, the severity of it, as well as the likelihood of detection for risk quantification (for example continuous design FMEA - CFMEA, Advanced FMEA - AFMEA). The FMEA tools are widely used in the European automotive industry and are the most common method for risk prevention and analysis [208], [209]. The method creates a risk priority number (RPA) based on the main parameters severity (S), occurrence (O), and detection (D) [210]. The Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) draw a logical tree by mapping branches of consecutive events leading to an undesired outcome [211]. All logical branches leading to an error must be considered demanding expert knowledge of the subject matter [212]. In contrast to the ETA, the FTA considers probabilities for the consecutive nodes to mathematically determine the likelihood of an undesired outcome given the current conditions. In terms of quantitative risk analysis, the Probabilistic Risk Assessment (PRA) is currently state of the art [213]. The PRA relies heavily on historical data and is often used in the context of reliability and safety engineering [214]. The probabilistic risk assessment may be influenced by an FMEA, ETA or FTA to create the risk model [213]. In terms of an early-stage use of the PRA, a functional description of the product performance is considered a useful starting point for PRA-based models ([215]). Functional models represent a form-independent blueprint of a product that can be derived early in the conceptual design phase from high-level customer needs [216], [217]. The risk in early design (RED) method builds upon prior work related to the function-failure design method (FFDM). The presented method derives the failure potential from a series of subsequent matrix multiplications (see Figure 2-5). The method connects functions to components (EC) and components to failures (CF) [218]. The RED method has been invented since other existing methods to date require mature design prospects to assess the implicated risk [219]. The method combines historical failure data with functional models to create an early-stage perspective.

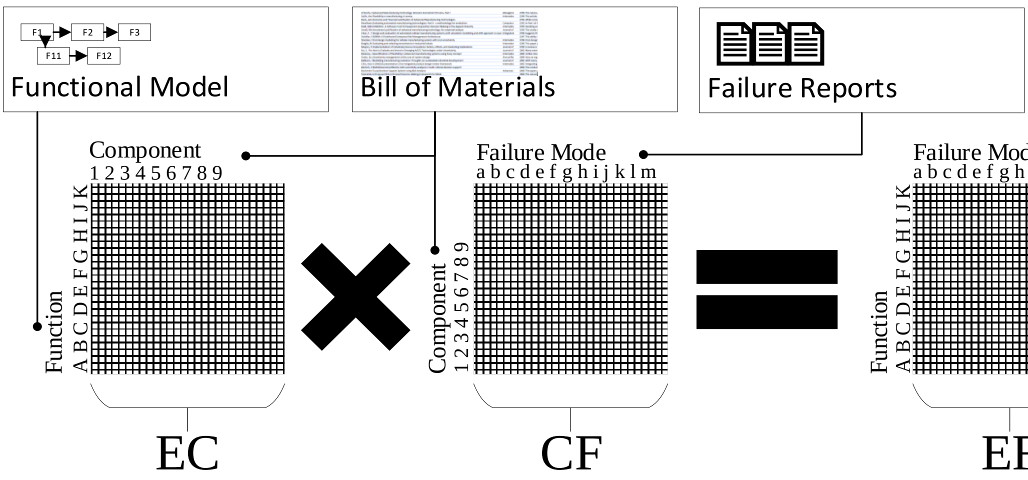


Figure 2-5: FFDM method as the basis of RED [213].

Therefore, the proposed method focuses specifically on a mathematical relationship between the function and risk of a product at an early-design stage [213]. The last approach towards risk mitigation is the so-called Robust Design Principles (RDP) method. The approach is an attempt of a collection of good design principles leading to robust design [220].

Overall, a significant amount of knowledge has been accumulated in the area around risk/ uncertainty mitigation and assessment. Previously, an endogenous perspective for the thesis was established. In terms of uncertainty manifestations of early-stage decision-making, several occurrences are present. In many of the risk tools, the necessity for a functional abstraction of the actual process is noticeable. For multiple cases, however, the tool requires an actual design concept as a basis to be used. For the research aim, however, the design of the automation system is unknown at an early stage. The second problem is access to historical data. The problem was found to be due to the two main issues of data sensitivity (automation means a competitive advantage for the companies) as well as the lack of recorded/available data for intelligent automation. The combination of missing design information and a lack of historical data creates a novel problem for early-stage decision-making. The consequent assumption is that at least two models must be created to mitigate the impact of missing data by modelling related uncertainties. The lack of existing data drives an expert knowledge-based approach.

C. Expert Knowledge

The abstraction of expert knowledge is a scientific methodology commonly applied in fields with no access to data or unreliable statistical data. Extracting expert knowledge is used to quantify uncertainty about the parameters of the subject matter [221]. The formalised and documented procedure for expert knowledge extraction is called *expert elicitation.* Main critics about expert elicitation are concerned with the verification of extracted expert knowledge. Additional measures should be taken to validate the expert knowledge and prevent an expert bias or heuristic biases during expert elicitation [222]. Tversky and Hahnemann have published an extensive amount of publication on the matter of heuristics and biases (see for example [223], [224]). A study by Kynn finds that one of the most critical factors is related to expert judgment under uncertainty [222]. Additionally, different approaches have been investigated to experiment on eliciting expert probabilities [225]. Main biases are related to risk assessments where the exposure of the expert to negative outcomes may lead to illusory correlation with factors and probabilities, as well as overestimation and underestimation when judging conjunctive/disjunctive events respectively. To prevent false expert input, the DELPHI method was developed to consolidate the views of a structured group of experts iteratively. The method passes back the inputs of other experts to encourage a revision of previous answers. Over different iterations, a consolidated expert opinion may be formed

[226]. The accumulated knowledge from the literature review will now fuse into a reflection on the presented literature.

2.4 Literature Review Gaps and Framework Requirements

Although, significant progress has been made regarding the analysis of a production task, the issue of *transferring human tasks* and introducing measurements allowing *mapping* of *human tasks against automation functions* has not yet been solved sufficiently. Several authors have contributed to the decomposition of human tasks and how to add additional detail to the presented investigation. Specifically, *an increase of granularity* seems to *affect the reproducibility of task analysis tools* and *has been criticised throughout* the existing *task analysis literature*. A high number of publications focuses on task complexity. From an automation perspective, however, contributions are required to connect the existing knowledge to automation decision-making. Especially, to understand how the complexity of a human task drives the complexity of an automation system. Therefore, the understanding is shaped that *an increase in task complexity* influences the automation system *demanding for more autonomous and intelligent systems*.

From the other direction, researchers have looked into *specific models to simulate task functions with interdependencies and model automation requirements* (for example [227]). The findings support that the current research environment focusses either on process factors or human factors. Even though generic findings still apply, the *strategic research* for automation implementation needs connections to more detailed levels and has become *outdated in the context of smart technologies*. The *product and process design techniques* are using data not available for the early-stage decision support and, therefore, can only be applied in later stages of the decision support. Furthermore, the *consideration of levels of automation* should be made within the thesis, in light of the development in human-robot collaborations.

The focus of the *technology selection* research community is primarily on the methodology of the mathematical problem evaluating subjective and objective criteria. Technology selection appears to be particularly useful for later stages of the automation decision process. *Early-stage decision* approaches use costing methods based on highly uncertain data (for instance design assumptions), and neglect process or human factors. The research body related to the early-stage decision support is found to be particularly small. The research body indicates a big gap for the early-stage decision-making support for intelligent automation. Similar findings have been pointed out in other research papers (for example in [228]). The reflection on the literature review will be used to create a methodology to fulfil the remaining research objectives. The following research gaps arise from the literature which will inform the methodology:

The *main gap* is related to an *early-decision support framework for intelligent automation*, which complies with the following additional research gaps. It arises from the assertion made in previous introduction chapter. The first additional gap is that currently, a variety of early-stage decision support methods require an understanding of the process design for cost and risk prediction. One key characteristic of the early-stage decision support framework is, therefore, that the *developed solutions would purely rely on the available task analysis (HTA) and standard operating procedure (SOP) input*. The second gap is a risk assessment trend in related areas pointing towards a *functional approach for risk determination*. Reason for a functional approach is the time between the decision-making process and the availability of design data. Decoupling the decision-making approach from design data by using a functional approach increases the usability of the decision-making process for early decision stages. A hierarchical task analysis is a basis for the structured analysis and design technique (SADT/IDEF0) used for a functional process abstraction to date. The process description is developed by experts and, consequently, highly affected by the individual expert. Accordingly, there is a *need for a systematic way of transferring knowledge from an HTA into functional task model for automation*. In terms of the decision-making process, different strategic papers accumulate factors important for implementing automation. Hence, a good understanding of critical decision factors has been accumulated for standard automation but needs updating to reflect smart technologies challenges. The following research gaps associated with the development of early-stage decision support for the implementation of intelligent automation need to be addressed, wich arise from the previous assertion:

- ➢ *Development of an early-stage decision support framework for the implementation of intelligent automation*
- ➢ *Design information should be unnecessary for the usability of the developed framework.*

- *The framework should extend currently used risk assessment methods by modelling the functional risk of a human task for automation based on expert knowledge. The motivation is to conduct probabilistic assessment via expert elicitation using methods to mitigate related uncertainties.*
- *The extraction of task information utilises process attributes to decrease variability introduced by experts and increase speed in creating a functional task abstraction model for automation.*
- *A quantitative investigation of critical decision factors updating the standard automation perspective should be carried out, as well as elicitation of smart technology experts towards intelligent automation.*

Based on the requirments identified from the literature review, the next chapter presents the research methodology to address the objectives.

3 Methodology

"We didn't set out to be educators or even scientists, and we don't purport that what we do is real science but we're demonstrating a methodology by which one can engage and satisfy curiosity." – Adam Savage

The previous chapters have introduced the reader into the research environment and presented a comprehensive state-of-the-art literature review to identify shortcomings in the research environment. More specifically, the need for a decision support tool at an early-stage for the implementation of intelligent automation has been identified. The indication of a research gap related to the early-stage decision support for implementing intelligent automation has led to a review of early-stage assessment methods. Since the only available source of information at an early stage is the current manual process, methods to mitigate the uncertainty and assess the risk of the intelligent automation project have been investigated. The current research indicates a requirement for a functional abstraction enabling the assessment of the implied risk. However, due to unavailability of historical data, the functional abstraction in the investigated problem cannot be informed by historical data and must be fed by an expert elicitation. The collected literature informs that precautionary measures must be taken during the extraction of expert knowledge (DELPHI method) and after to verify the collected probabilistic input (validation of experts). The requirement of expert elicitation, however, might drive the complexity of the conducted research. A connection of the expert input might drive probabilistic methods to further reduce the uncertainty of the intelligent automation assessment.

Additional investigations will later point out challenges specifically related to the arising intelligent automation (lack of cost data) and connected uncertainties. The additional investigations will be presented in chapter 4. The unavailability of system design information and a lack of historical data necessitates the choice of methods suitable in mitigating the related uncertainties.

This chapter is dedicated to explaining the research methodology investigating the remaining research objectives. The research methodology represents the distinct and careful argumentation for a selection of an approach, methods and techniques best suitable for the illumination, identification, analysis and solution of the given research problem. In other words, the methodology explains the way that the methods are used and linked together to answer the resreach questions. The chapter is logically divided into three different sections. Section 3.1 presents the research stages. Section 3.2 shows how specific research methods are applied according to the presented research stages and objectives. The last section 3.3 summarises the methodology chapter.

3.1 Research Stages

The research stages represent the overall structure of the applied methodology. Naturally, a difference between experimental research, simulation-based research or applied research exists. Focusing on different disciplines, however, similarities among different types of research projects have been detected by Blessing and Chakrabarti [229], which come to the conclusion every investigation typically consists of three parts:

- Descriptive Study (Stage 0): Examination of the current situation.
- Prescriptive Study (Stage I): Understanding to develop support for improvement.
- Descriptive Study II (Stage II): Developed support evaluated and validated.

In order to explain the three parts in the present study, the view adopted is displayed in Figure 3-1: Research Stages and Objectives. Starting with the descriptive study in stage 0, a basis is established informing the further course of the research project. In stage I specific problems are addressed, which will finally be evaluated in the research stage II. The following sections describe the structure of the stages in the thesis. Adding a detailed description in the following sections, the focus points are represented using the research questionss, which can be found in Table 3-1 accordingly. The applied research methods according to the research questions can be found in section 3.2. The section is organised chronologically and explains the research stages 0, I and II according to Figure 3-1. The sub-section starts with the first research stage 0.

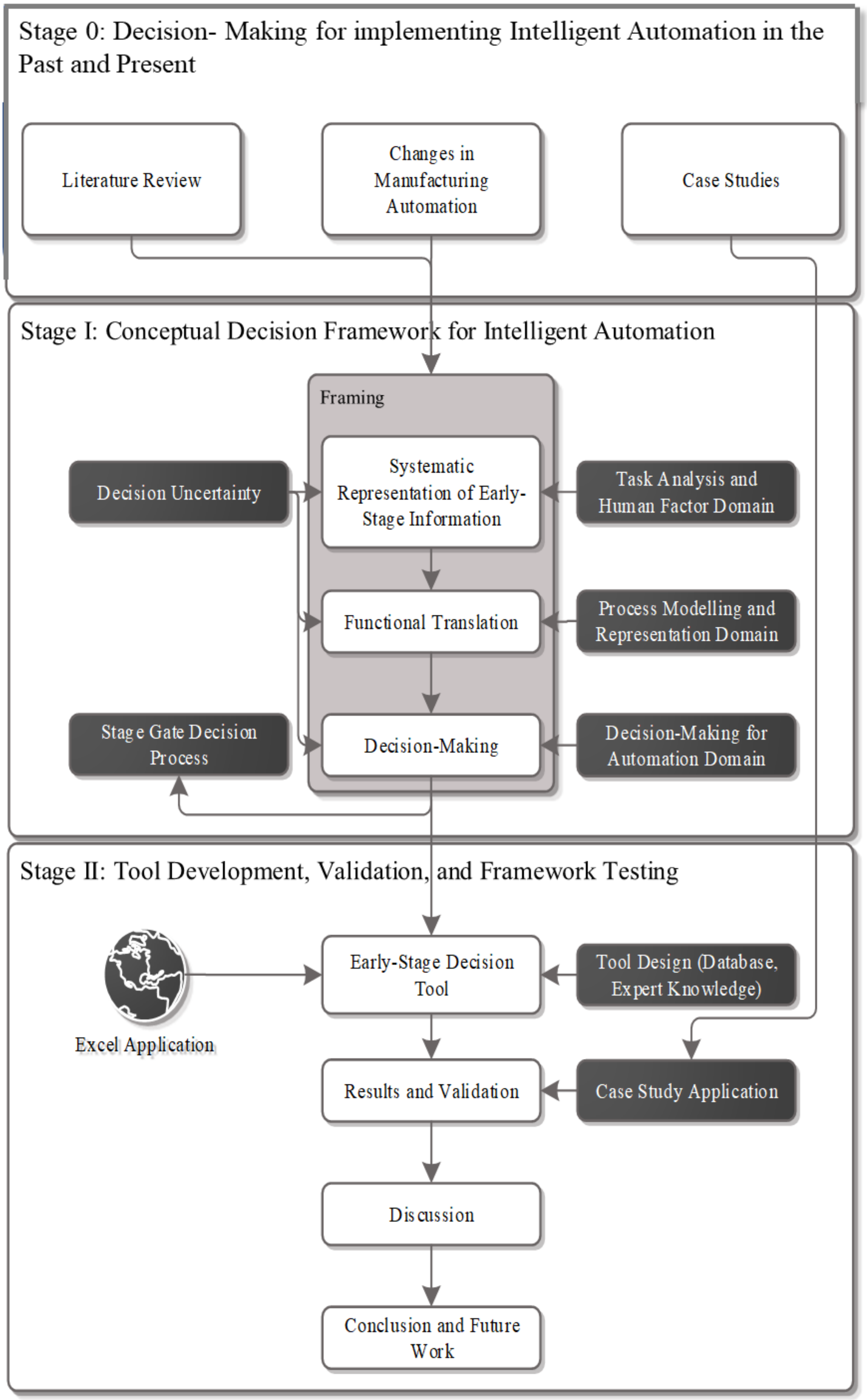


Figure 3-1: Research Stages and Objectives.

3.1.1 Stage 0 – Descriptive Study

The first research phase is the collection of available information to describe the current research environment (Chapter 2). Therefore, publications and literature are accumulated and described representing automation decision-making in the past. Naturally, a disconnection arising from Industry 4.0 using smart technology to increase the flexibility of modern automation has been created. A solid representation of the current problem requires both, focus on the past and the present. Combining past and present knowledge allows to fully examine the current situation. As a response to the requirements, additional studies were conducted.

The information is complemented by an examination of the current experiences related to integrating smart technologies and systems in manufacturing businesses. The purpose of the examination is to add information about intelligent automation challenges through an expert survey and workshop (section 4.1). Therefore, Chapter 4 expands the knowledge about how the systems have evolved from automation systems in the past towards smart systems in the context of Industry 4.0. A synthesis of knowledge will build the foundation of the thesis describing the current intelligent automation conditions.

3.1.2 Stage I – Prescriptive Study

Stage I uses the understanding of the descriptive research to aid the improvement of the current situation. Thus far, the results have implicated a research gap with regards to the early-stage decision support for the implementation of intelligent automation. As a consequence, the stage focuses on establishing a framework, which identifies important features based on limited information to aid an intelligent automation feasibility decision. As part of the establishment of the conceptual framework, the available information will be structured to develop a conceptual solution for the present decision-making problem. Based on the systematic flow of information and the identification of relevant information, the conceptual framework influences the development of a decision-support tool. The following stage aims to evaluate the prescriptive stage. The conceptual framework is applied to real case scenarios. The evaluation and validation of the framework are carried out using historical case studies and presented in section 3.2.3.

3.1.3 Stage II – Descriptive Study

Stage II is the last of the three major phases within the thesis. The main function is an examination, whether the operationalisation of the conceptual framework can be achieved, and the corresponding results can be validated. Once the decision support tool has been developed, the results must be evaluated to confirm that the research questions have been achieved. A real-life application scenario based on collected business cases is used for the evaluation. The results are compared to the current decision mechanism of experts and the use of a developed validation framework for the decision models.

This section has described the overall structure of the research reported in this thesis. Initially, the research stages describe the environment and add additional knowledge to contribute to a better understanding (Stage 0). The understanding serves as the basis for the conceptual framework to support decision-makers with the implementation of intelligent automation (Stage I). Based on the conceptual framework, the work is operationalised and evaluated using real case scenarios (Stage II). The stages form the research methodology. The following section discusses the methodology to achieve the research questions presented in section 1.6.

3.2 Research Methods applied to Research Questions

This section discusses, where generic research methods are applied and how the different methods work together to achieve the objectives. Table 3-1 exhibits the research questions as a reminder of the introduction section (see Chapter 1) and describes the methods used. The questions are listed to chronologically explain the research methodology.

Table 3-1: Research Stages, Questions and Methods Applied.

Research Stage	*Research Question*	*Description*	*Method*	*Chapter*
0	1	Understanding the Human Task for Automation	Literature Review	2
0	1	Process Representation Models	Literature Review	2
0	1	Automation Decision-Making	Literature Review	2
0	2	Trends in Early-Stage Decision-Making for Automation	Literature Review	2
0	2	Identification and Quantification of Critical Factors for Automation	*Text Mining*	6
0	2	Changes in Manufacturing Automation	*Survey and Workshop*	4
1	3	Systematic Representation of Early-Stage Information	*Framing Process*	5
1	3	Synthesis of Information for Decision-Making Process	*Framing Process*	5
1	4	Extracting Critical Success Factor Related Uncertainties	*Framing Process*	5
1	4	Decision Modelling	*Framing Process*	5
2	5	Development of Decision-Making Tool	*Mathematical Modelling and Programming*	6
2	5	Case Study-Based Use of Framework	*IDEF0/ Bayesian Network Validation Framework*	7

The research methods are discussed next according to the research stages and questions. The following section introduces the research methodology used for stage 0. Stage 0 aims to understand the current research environment. The following section shows the methods applied to support the thesis starting with the literature review (Chapter 2).

3.2.1 Stage 0 – Descriptive Study

As previously pointed out, the Descriptive Study is divided into two logical steps. The description starts with the identification and quantification of critical success factors for the decision framework. Past and present developments are extended by merging the quantitative decision factor study with expert knowledge about smart technology.

A. Literature Review

This part of the research methodology corresponds with the research question 1 and 2. The literature review, therefore, started with the investigation of publications in four core areas of the presented thesis. The four core areas are understanding the human task, process representation models, automation decision-making, as well as trends in early-stage decision-making for automation. Consequently, the core areas have been initially investigated with a careful review of the current literature and summarised in this context. After the literature review, the knowledge-base was extended via an additional investigation.

To extend the existing knowledge about the current implementation of intelligent automation, a technology survey and workshop to update the current knowledge base is used. The following sections explain the methodology accordingly.

B. Changes in Manufacturing Automation

The objective is to identify changes in the manufacturing automation sector. Hence, a survey has been distributed to understand the current technological changes within smart technologies and how those challenges affect their implementation in manufacturing. The technology survey is later triangulated and extended by a workshop with other experts about the barriers and limits of smart technologies and systems on two different scales. To extend the knowledge from standard automation towards intelligent automation, the knowledge has been updated taking the approach depicted in Figure 3-2. The motivation for the selected setup is the lack of an intelligent automation expert pool and an arising opportunity from the European Co-FACTOR project[2] to consolidate the view of smart technology experts on the current situation. The idea is to gain knowledge about introducing intelligent automation by understanding the introduction of smart technology in manufacturing (see Figure 3-2). The gained knowledge about smart technology introduction problems and opportunities will then be translated into an understanding of arising intelligent automation problems.

[2] European Project under "Horizon 2020": Co-FACTOR project (Project-Number: 637178)

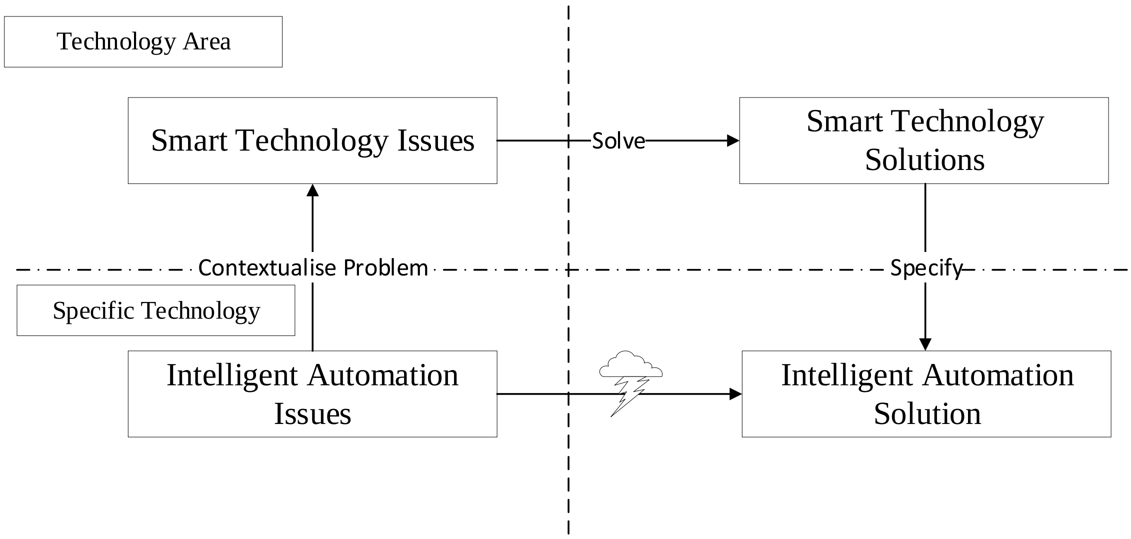


Figure 3-2: Methodology Of Intelligent Automation Solutions.

In this way, understanding can be shifted from a standard automation application towards intelligent automation by considering smart technology issues.

3.2.2 Stage I – Conceptual Framework

The conceptual framework is developed based on the established foundation. The understanding gained at research stage 0 is summarised in terms of the implication for the decision framework. The remaining steps are a systematic representation of early-stage information, a synthesis of information for decision-making, an extraction of critical decision factors, decision-modelling, as well as the operationalization and validation of the subsequent framework.

The conceptual framework describes the connection to the environment, the situation and implications as well as establishes a way to aid the intelligent automation decision. The following points summarise the accumulated knowledge.

A. Systematic Representation of Early-Stage Information

The starting point for the conceptual framework is the systematic representation of early-stage information. The framework summarises the available information at an early-stage for the decision-making process. The initial stage will be mostly informed by the achievements of previous research with regards to task analysis and human factors. Based on the available information, reasons will be collected about the importance of information for the decision-making process and how a systematic representation can be achieved.

B. Synthesis of Information for Decision-Making Process

The existing early-stage information establishes a ground upon which the decision process is based. A logical way to synthesise the existing information must be constructed. Due to the limited amount of available data at an early stage, this logical step must ensure that no crucial information is missing for the decision-making process. The synthesis shall, therefore, be informed by the process representation and modelling literature to ensure latest methods have been considered. It will be taken into consideration when the fusion of existing information into the process representation and modelling domain is explained. A good synthesis of the current information will allow a basis for the decision-making process. Even though all the possible early-stage information has been logically modelled, the importance of different factors and causal relationships cannot be fully obtained.

C. Extracting Critical Success Factors Related Uncertainties

After the required information is presented in a structured manner from an early-stage perspective, specific critical decision criteria must be extracted, and relations identified, which build the foundation of the decision-modelling process. However, a selection of alternatives can only take place once the framework is developed based on a synthesis of available information. At the specific research stage, the information basis had not yet been established. The detailed presentation of methods selected on the established information basis will, consequently, take place at a later stage in this thesis and is not necessary for now. The information to take from this section is that critical success criteria must be established prior to the decision-making process. The existing critical success factors will lead to decision-modelling.

D. Decision Modelling

Similar to the previous section, decision-modelling requires synthesis of information. Additionally, decision modelling is based on selected critical decision factors extracted in subsection (C). Based on the accumulated knowledge of the previous steps, the existing information enables reasoning about the most appropriate decision-model. Critical success factors for the decision-modelling are naturally the presence of historical data and uncertainty among decision factor- related data. The decision-model is the last step of the framing process. Establishing the conceptual framework enables the operationalisation of a decision-making tool. The research methodology of the decision-making tool can be found in the subsequent section. The following methodology will be partially based on the knowledge arising from chapter 4 . As a consequence, the realization details will not be presented in the following sub-section.

3.2.3 Stage II – Realisation of Conceptual Framework

From the previous objectives, only the operationalisation and validation objectives remain. According to the conceptual framework (chapter 4), in a first step, the process must be abstracted into functions based on the knowledge originating from the task analysis and human factors domain. This step describes which parts of the initial information is needed to fully extract information for decision-making. The structure is based on the review of task analysis literature. After the crucial information has been identified, a fusion of critical knowledge must take place. The provided information will then establish the assessment of critical success factors based on the existing information and the related decision modelling for the assessment of intelligent automation. A more detailed description is given later and is not required for the understanding of the following chapters at this point. The description is partially based on information originating from the conceptual framework. More information can be found in chapter 4.

3.3 Summary

The methodology chapter has given an overview of the methods applied to anwer the research questions. First, the different research stages have been presented in the first part of the chapter to introduce the logic of a descriptive study, followed by a prescriptive study, justified by another descriptive study. After the overall structure, the research methods applied to answer the research questions have been discussed. The methods and justifications will be documented in more detail in the related chapter. The main objective of this chapter was to present the methodology of the thesis. The following chapter will start with the descriptive study as presented in subsection 3.2.1. The subject of the subsection was using a hybrid approach: the identification and quantification of critical success factors of a manual and text-mining review, as well as a workshop, to present changes in manufacturing automation using smart technologies.

4 Conceptual Framework

"You don't have to be a genius or a visionary or even a college graduate to be successful. You just need a framework and a dream. – Michael Dell

As previously pointed out in chapter 3 (methodology), the literature review has identified shortcomings among the current automation implementation literature. Evidentially, however, a lot of the presented work is related to standard automation. The introduction section 1.1 states that automation is being criticised as not sufficiently flexible. This chapter was motivated by the idea to learn about the current smart technology environment and extend the existing knowledge. The framework will be updated by implementation issues of smart technologies in the first part of the chapter. The study examined how the introduction of smart technology increases the automation complexity by introducing additional limitations and barriers. The following section starts with the study. Based on the smart technology findings, the conceptual framework will be developed.

4.1 Changes in Manufacturing Automation

The following sections present the results gained from the applied methodology presented in section 3.2.1. The results focus on the question presented as part of the introduction section updating the knowledge about implementing intelligent automation in manufacturing businesses. So far, a numerical extraction of factors and their importance based on text mining has been presented. The second part focuses on the introduction of smart technologies.

4.1.1 Approach

The overall structure of the investigation is documented in a chronological manner according to how the research was conducted. Firstly, the survey results will be discussed in detail before the results gained from the conducted workshop are presented. The following section introduces the approach to investigating the implementation of smart technology in manufacturing businesses.

A. Expert Sample

The opportunity to gain the information had been recognised during involvement in the Co-FACTOR project, which identified 130 experts listed in an expert database. The Co-FACTOR project aims to initiate a European smart technology community. The experts are currently working on European projects and have gained experience in integrating smart technologies and manufacturing systems, such as intelligent automation. The responses to the survey are collected using the commercial online survey platform 'SurveyMonkey'[3], which allows the users to create an online link. The web link is circulated using email details of the expert database. The responses are collected from twelve different countries (Germany, France, United Kingdom, Spain, Italy, Portugal, Greece, Sweden, Austria, Belgium, Ireland, and Switzerland) from a European expert databank. Despite the fact that several leading countries in the area are missing (e.g. USA, Japan, Russia, China, South Korea, etc.), the European experts have been reportedly involved in global projects as the automation community is globally connected. It is assumed that the evaluation of the experts will, consequently, lead to a relevant result.

B. Evaluated Technology

An intelligent automation (IA) system contains smart technology like smart proximity sensors and force and torque sensors, which are typically linked to machine learning algorithms. The flexibility of such systems enables a higher product quality than conventional solutions as part of IA. The survey uses specific definitions of the technologies as a basis for the questions asked. The results show a structured answer to where the different technologies are currently set in terms of their implementation from a technologies expert's perspective. The thesis will not discuss all the related questions from the survey (Ref Green Paper for the full survey) but questions to evaluate the experts and one question about smart technologies' and systems' limitations and introduction barriers. The next section explains how the survey was conducted and the strategy used.

C. Survey Methodology

Both qualitative and quantitative approaches were adopted to provide insight into the technical perspective of implementation issues for smart technology and manufacturing systems. The quantitative approach is used for the survey to gain a wide range of opinions,

[3] https://www.surveymonkey.net/home/

whereas the qualitative approach (workshop) is used for triangulation and to gain in-depth knowledge. Due to both, the limited amount of information (technical issues, current integration challenges) and the customized nature of manufacturing systems (heterogeneity), an investigation of relevant smart technology and the integration of smart technologies to form manufacturing systems is proposed. The web survey is divided into two different parts. The first part collects information about the expert pool to validate the selection of respondents (see Table 4-1). The results can be seen in Figure 4-1.

Table 4-1: Questions for Expert Evaluation

Question	*Evaluating the experts*
Q1	Is your current role industrial or academic?
Q2	Would you consider yourself an expert in smart technology?
Q3	Please indicate the number of years' experience you have related to Smart Technology
Q4	What kind of perspective do you have on smart technologies?

Ten of the twelve countries are within the twenty technologically most developed countries in Europe [304]. The experts are part of current European projects related to smart technology and have, therefore, been listed as experts in a European database. Part of this database are industry facing experts from both, academia and industry. Reason for the second question of self-identification has been purposefully created as validation of the existing expert-database. Possible reasons for occurring negative responses might be due to the Dunning-Kruger-effect, which states that the underestimation of capabilities rises with the expertise ('expert bias') [305]. Out of those identified 130 experts, 63 experts responded to the survey request (Figure 4-1).

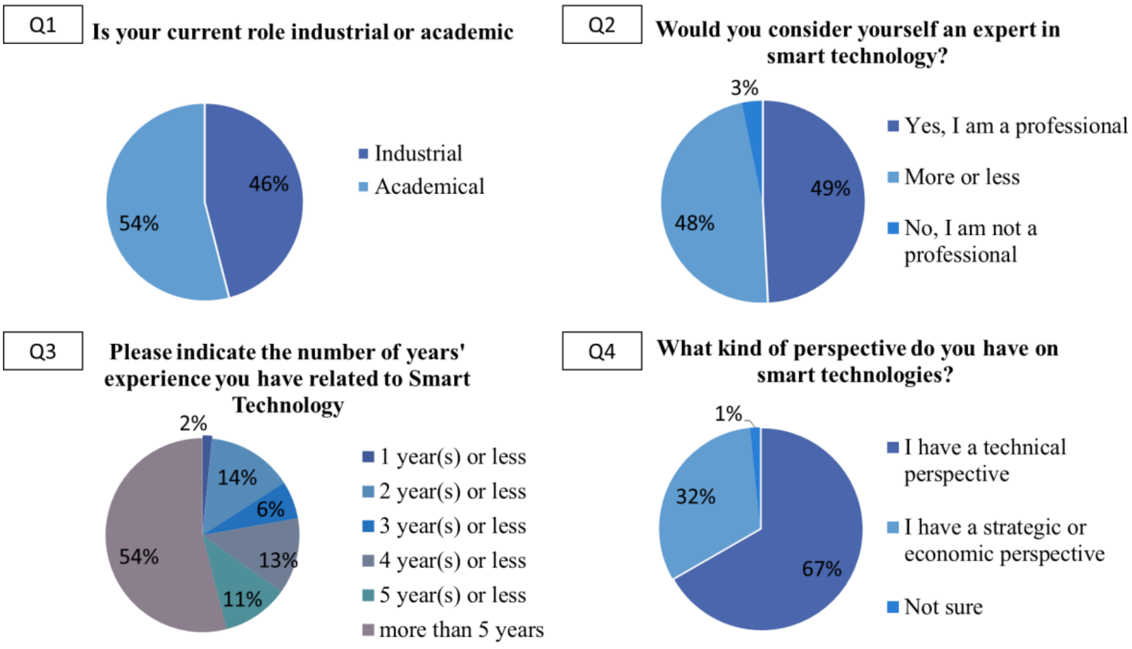


Figure 4-1: Expertise of respondents.

67 percent of the respondents claim to have a technical perspective while 32 percent have an economic/strategic one on manufacturing systems technology; 29 (46%) respondents were industrials, whereas 34 (54%) were academics; more than half of the experts have been working within the specific area for more than 5 years.

The second part of the survey focused on gaining information about related technologies and systems. A starting point for the investigation was to rate different smart technologies. The hope was to stimulate a reflection on the barriers and limitations later by creating a list of technologies currently used. The questions were mainly related to standard technology categorisations established in the area to rate the maturity and development stage of technologies and systems, but also to standard measurements like the importance of technologies. During the questionnaire stage, no differentiation was made between smart technologies and systems to avoid confusion and the increase in questions' complexity for the respondents. The innovation stage, the meaning in the context of smartness, the development potential, the time to full market readiness, a ranking of importance of the smart technologies and systems as well as the significance were evaluated. A comprehensive review of the questions in an investment context can be seen in a green paper by Micheler et al. [306]. At the end of those questions, a generic question was introduced about the implementation barriers for smart technologies and systems.

Table 4-2 shows the question circulated and evaluated for the smart technology study important with regards to the thesis.

Table 4-2: Questions for Smart Technology and Systems Evaluation.

Question	*Evaluating Smart Technologies and Systems*
Q5	What would you consider to be the main barriers to the development and introduction of smart components and technologies?

In addition to the online survey, a workshop was held for triangulation and to gain in-depth knowledge about the experts' responses. The methodology for the workshop is presented in the following section.

D. Workshop

In addition to the distributed survey, an expert workshop triangulated the results using experts for a workshop to ask about the integration of smart technologies for intelligent automation. The workshop was held on October 13, 2016, in Brussels, Belgium. Four consultants, eight academics and five industrials participated in the workshop (17 experts in total). In a first iteration, the experts were asked to note down specific barriers, limitations, short- and long-term impacts of smart technologies. The purpose was the collection of a wide range of suggestions for those categories. The second iteration is used to weight the specific technologies. The expert is confronted with the opinion of other respondents' opinions and had the chance to specifically give points to the collected statements. The researchers have not given any rules or limits about the point system. However, only one point per expert can be given for a suggestion. The workshop was focusing on different scales. A technology scale and a system scale to compare the categories and scales later and specify the problems as a basis for the following research. The following sub-section introduces into the survey results, which arise from the research approach. The presentation starts with the survey results.

4.1.2 Survey Results – Introduction Barriers

However, not all the questions are presented in detail but only the last question (Q5), which contributes to the research aim. For the introduction barriers, the question was designed to give the experts a selection of possible answers. The possible answers are presented in Table 4-3. In response to the question Q5 in Table 4-2,*'What would you consider being the main barriers to the development and introduction of smart components and technologies?'*, 54 percent of them claimed the barrier would be the ease of implementation of those technologies and 51 percent of the participants stated that one of the highest barriers would be the insufficient introduction of industrial standards for smart technologies. In addition to that, Experts pointed out that the compatibility with existing machines is a further barrier (both ~46 percent). At the same time, approximately a fifth of the respondents claims that smart technologies do not offer sufficient flexibility. The results, therefore, suggest integration barriers most crucial for the introduction of smart technologies in manufacturing. The results correspond to the current research environment. Platform strategies and industrial standards are identified as important informing the compatibility with existing machines and increase the ease of implementation (see for example [307]).

The next category is related to the organisational perspective of a company. Missing management leadership/prioritization, as well as R&D funding and human resources, are found to be barriers to the implementation of smart technologies. Management and leadership prioritisation have been frequently identified throughout the body of literature as a possible introduction barrier for smart technologies. The barrier may origin from a lack of decision support for decision-makers and, consequently. the decisiveness of the management. No decision-support means the prioritisation of projects may be too risky and, therefore, leads to diversification of risk through multiple projects.

From an information and communication technology (ICT) perspective, the insufficient integration of communication technologies (~43 percent), the insufficient know-how (~40 percent), and a lack of data processing technology integration (~37) were mentioned. Only a minority of experts stated that the development of new sensors and actors or the data processing capacity is a barrier to the introduction and development of smart technologies in a manufacturing environment.

Table 4-3: Introduction Barriers for Smart Technologies (Q5).

Main barriers for the introduction and development of smart technologies	Share of respondents
Ease of implementation	54%
New industrial standards	51%
Compatibility with existing machines	46%
Management leadership/prioritization	46%
Integration of communication technologies	43%
R&D Funding	43%
Human Resources	43%
Know-how	40%
Integration of data processing technologies	37%
Flexibility of smart components	20%
New sensors and actors needed	14%
Data processing capacity	14%

The results of the introduction barriers are further explored in the workshop results in section 4.1.3. The workshop has been introduced to validate the results and present more detail to the barriers, limitations as well as identify long- and short-term impacts of smart technologies on manufacturing.

4.1.3 Workshop Results

The executed research aims to investigate and discuss the current landscape and identify potential barriers and limitations of integrating smart technology into manufacturing systems. The workshop results are presented in Table 4-4. In a first round the 17 experts were asked to note down specific barriers, limitations, short- and long-term impacts of smart technologies. A second iteration gave the experts the opportunity to give points (weight) to those specific statements. The numbers indicate how many times the experts voted for the concept. Based on the combined results, several points can be discussed. A comparison of the two results related to the system scale reveals scale differences.

For a novel and complex project, several risk-related issues were pointed out for companies implementing smart technology in manufacturing systems. The main barriers to introducing smart technology into manufacturing are technical trust, skills, ownership data, semantics and the awareness of such technologies. Problems related to technical trust cannot be avoided with novel systems. However, such barriers also identify issues with knowledge transfer and a more practical requirement engineering approach, which might increase the confidence in a reconfiguration of customised systems. On a smart technology scale, one can see the barriers include proving the return on investment (ROI). Once the smart technology has been developed, the first problem is the justification of technology integration and usage within a smart manufacturing system. For most of the new technology as part of the manufacturing system, quantifying the ROI has been reported a barrier to the implementation. Despite significant contributions in the costing area, a generic and pragmatic approach to justify smart technologies has not yet been solved, according to the smart technology experts. Other barriers are privacy issues, the legacy system, and data access.

After the barriers of the smart technologies and systems, the experts focused on the limitations of both, technology and system level. Concerning are the quality of data, the technology change acceptance, the availability of data, and the heterogeneity (in hardware). Main limitations on a systems scale are standards, cost structure and compensation schemes, intellectual properties, and protocol translation. When smart technologies are introduced to an existing system, the industry faces additional compatibility challenges. Those challenges, however, seem to play a role in the current research as technology strategies and platform issues have been recently presented in publications related to different smart technologies [307]. However, the experts still recognize the compatibility as a limitation for technology introduction implying a transition of knowledge from universities to the industries must take place. The discovery corresponds to the other identified barriers like awareness, technical trust, and technology change acceptance.

Table 4-4: Technology Barriers, Limitations and Impact.

Category	Smart Technology	Weight	Smart Systems	Weight
Barriers	Proving ROI	4	Technical Trust	6
	Privacy Issues	2	Skills	2
	Legacy System	2	Ownership Data	2
	Data Access	1	Semantics	1
			Awareness	1
Limitations	Quality of Data	3	Standards	4
	Technology Change Accpetance	3	Cost Structure and Compensation Schemes	4
	Availability of Data	2	IPR	1
	Heterogenity (in Hardware)	1	Protocol Translation	1
Short-Term Impact	Value of the Data	1	Increased Reuse of Equipment	3
(< 5 years)	Increase in Small Players	1	New Business Models	2
	Reduce Resource Requirements	1	From Product to Service (Equipment)	1
	Reshoring of Manufacturing	1		
Long-Term Impact	Self-adaptive Factory	3	Increased Flexiblity, Sustainability and Efficiency	1
(>5 years)	Worker Satisfaction	1	Change from Product Society to Service Society	1

4.1.4 Findings

This sub-section critically reviews the challenges and opportunities for smart technologies and systems. The responses of 63 experts who work directly on the development of smart components and systems across Europe have been analysed. The responses were collected via a survey and triangulated with a workshop (similar approaches have been proven reliable, see for example [308]).

The ease of implementation is rated as one of the crucial challenges for the integration of smart technologies. Despite countless contributions in the domain, not much research has been presented over the last 5 years to ease the implementation of smart technologies on all different levels from a holistic systems perspective. Current research eases the integration of heterogeneous sensors; however, a wider manufacturing systems' perspective has not yet been taken and addressed. Research is still working on a holistic definition of industrial sensors on a systems integration level [309].

Sensors are just one of many different additional components a manufacturing system is usually equipped with. Additional tool components such as, for example, welding tools or fastening tools exist, which must be controlled using different controllers and data exchange protocols. Therefore, a need for increased harmonization topics is pointed out, for example, an extension of standard communication protocols and hardware interfaces or technologies such as distributed network controls. Comparing the high-level questions of the survey and the workshop results with regards to harmonization topics, the responses seem to be consistent to a certain degree.

The results suggest that the complexity and capability of smart systems are increasing, which corresponds well with indicators from recent publications [310]. While some smart systems challenges are currently being investigated (for example, compatibility issues are being addressed via technology platforms and technology strategies), other challenges remain largely unsolved (for example, smart technology implementation support and harmonization).

At the early stage of technology adoption decisions, Return On Investment (ROI) calculations and estimations might not be feasible due to missing cost information for new technologies. The answers prove a quantification of the benefits and costs of novel technologies difficult and express a lack of decision support for both, the early assessment and introduction of smart technology in manufacturing businesses from a managerial perspective (i.e. business case and risk assessments). Therefore, new ways to introduce sophisticated risk and cost management for high-technology companies are needed. A reduction of risk may also be achieved by the increased reuse of smart technology equipment. In the smart technology domain, the risks of introducing smart technologies can be mitigated by a more sustainable approach that allows the company to decrease risk through re-using purchased equipment. This means that the risk is reduced by re-using already purchased equipment based on the underlying manufacturing function.

In combination with the also occurring problems of standardization, the main barriers to smart technologies are preventing companies from achieving the promised strategic advantage. Further underpinning reasons for reoccurring challenges appear to be an unawareness of specific emerging smart technology capabilities and their benefits as well as a lack of systematic knowledge-transfer instruments from academia to industry. The resulting impression points towards main challenges related to overcoming earliest technology introduction stages. The respondents highlighted a lack of sufficient funding instruments for early technology development.

Based on the findings from the experts, three key recommendations can be concluded on how the wider and faster uptake and implementation of smart technologies can be supported in the future: (1) need to improve knowledge transfer from academia to industry; (2) decision makers within the industry require a robust decision support framework to assess the benefits and risks of introducing smart technologies and systems; as well as (3) an increase of harmonization efforts in manufacturing (standardisation and re-use of equipment). Addressing the three challenges will strengthen the confidence in smart technologies, help decision makers to understand related risks, and support sustainable innovation. In the longer term, a high degree of confidence among the experts was demonstrated that smart systems will increase the overall competitiveness of companies.

Estimated effects are

- a dramatically reduced reaction time to changing environmental conditions,
- higher efficiency through increased technology awareness,
- and rising productivity through better automation of decision tasks congregating to ensure future manufacturing to be on a globally competitive level.

After the reflection on quantifying critical decision factors and the view on automation by adding knowledge from the smart technology domain, a chapter summary will set the work into context.

4.1.5 Summary

This section summarises the contributions arising from an update of factors causative to the implementation of intelligent automation. *Even though costing has been identified as one of the main factors for the implementation of automation*, the approach seems *impracticable for smart technologies and systems justification* at an early stage (Gate 2). A lack of ROI data is reported as the likely reason as costs and benefits for customised and highly flexible solutions cannot be easily obtained. The experts *demand a more practical approach to smart technology introduction support*. The last point arising from an update of the current environment and expert elicitation is the importance of re-using manufacturing equipment. *The reuse of manufacturing equipment mitigates the financial risk of smart technologies*. Therefore, designing a system to identify a reuse case might be required; possibly through means of a technology's presentation to the engineer.

Section 4.1 has updated the view on the implementation of intelligent automation. In section 4.2, the framing process for the conceptual framework will be described. Section 4.3 will discuss the overall knowledge that has been accumulated to date and describes a transition of research stage I to research stage II. Section 4.4 of the chapter will then present the conceptual framework with regards to the early-stage decision support for implementing intelligent automation in manufacturing.

4.2 Framework Basis

Before the overall framework is presented, the literature review findings and changes in the manufacturing environment are collected to create a holistic picture. The following section starts with a representation of implications derived from the literature review.

4.2.1 Framework Requirements Identified from the Literature Review

This section will discuss relevant findings within the literature and their conceptual implications on the decision framework. The starting point for the following argumentation is the decision point for automation:

- Early-Stage Decision Support is required for business case evaluation.

A large and growing body of literature has investigated the implementation of automation in manufacturing businesses. Over the past decades, however, the publications focus either on later decision gates (see Figure 1-2) or on strategic automation decision support (Process and Product Design, Technology Selection, Automation Strategy). However, the generalisability of the literature with regards to intelligent automation is problematic. The problem originates from technological evolution. The next decision framework needs to investigate the implementation of intelligent automation from an *early-stage perspective*. The early-stage perspective significantly increases the uncertainty for the decision-maker due to the following points:

- Design information or historic information is required to assess technology cost and risk.

An investigation of the early-stage assessment literature in different areas reveals that the *majority of presented early-stage support relies on design information* or *historical* information (for example PRA, RED, etc.). The *aim* of the framework, however, is a *decision prior to the automation design stage (Gate 2)*. The *only information* available descends from the *manual manufacturing process*. *Decoupling* the decision *from design information*, however, significantly *increases the difficulty* of the assessment.

- High uncertainty with regards to the design information leads to a probabilistic approach.

The lack of design information leads to a more probabilistic approach initially decoupled from costing information. Despite the importance of cost considerations in general, the presented framework will *focus on a probabilistic assessment* for an early stage. The following reason is held accountable: The high uncertainty at an early stage increases the uncertainty for costing, *especially* if the *decision-making* is *decoupled* from *design information*. The *consequent assumption* is that a probabilistic risk assessment approach is more feasible for the assessment in the developed framework. As a consequence, it is argued in favour of a probabilistic assessment at the moment but will finally be concluded after the implications arising from ‘changes in manufacturing automation’.

- Transferring human tasks into a functional representation is required.

As demonstrated in the literature review, significant contributions have been made to the human factors’ domain. The presented literature identifies the importance of structural task analysis for automation and points out the significance of human factor considerations for the success of automation projects. Building upon the body of literature, a *new challenge is the systematic translation of human task information* for the implementation of intelligent automation. Core requirements for the method are:

- Systematic and fast
- easy to use
- reduction of analysts' influences
- sufficient information provided for early-stage decision
- differentiation between LoA (not automating, partially automating, fully automating the process)

At the same time, the framework should fit into the automation decision context presented within the current automation implementation literature domain.

- The framework should build up information to lead over to a detailed business case analysis.

From a more global perspective, the early-stage decision-support tool should collect information that strategically fits into the automation implementation context (and prepare a more detailed business case analysis for Gate 3 in Figure 1-2). The requirement ensures respecting the different stages of implementing automation. The collected information from an early-stage decision-support framework should be used to inform the design for automation stage, which subsequently should inform the technology selection and costing process. Even though the framework's context is prior to contributions of the main body of existing literature, important decision factors can be obtained to a certain extent.

- Strategic papers do not provide decision support with quantitative details to structurally aid the decision process.

A conclusive picture of critical decision factors for automation has been presented to date. And yet, what is known about the decision support factors is largely based on qualitative studies investigating the impact of different factors on the implementation of automation. The framework relies on an update of quantitative information to reason for the practical decision-making process. Based on the limited quantitative relationships demonstrated in the literature and updated information about smart technology introduction, it was decided in favour of an extended investigation (methodology section 3.1.1). The implications of the consecutive investigation (see section 4.1) are presented in the following section.

4.2.2 Framework Requirements Identified from Survey/ Workshop

Further implications arise from a quantitative perspective, where the current perspective on automation is updated towards intelligent automation. The following statements summaries the implications for the framework:

- The implementation of automation is focusing on a technical perspective.

Quantitative analysis demonstrates the focus of *decision criteria* on a *predominantly technical* perspective. The findings are specifically demonstrated with regards to the created clusters extracted from the current publishing landscape. The *results* of the *critical success factor investigation* via text mining *contradict* the *findings* of the *human factors domain arguing in favour of human factors consideration*. For the framework, a middle ground should be found. The *human task information* will be *used to mitigate the uncertainty effects related* to missing process design information via a *functional description of the manufacturing task*. Hence, human task information should be used to inform a technical perspective.

- Costing is a concern, but impracticable for early-stage decisions.

In addition to the technical perspective, costing and investment are the most frequent factors mentioned in the current literature. And yet, the knowledge gained from the smart technology *experts suggests difficulties in calculating the return on investment* related to smart systems. The experts are *concerned about predicting the costs of smart systems due to the complexity* and *novelty* created using smart technologies. The respondents point out impracticalities using a costing approach for early-stage decisions.

- A more practical approach for smart technology introduction support is required.

It is stated that a more practical approach is needed to justify the introduction of smart systems rather than relying on impracticable cost predictions at an early stage. At the same time, the *experts confirm* a *need for introduction support* for smart technologies by introducing new methods to manage risks. Therefore, the results from the study encourage a re-orientation of the decision framework towards a risk-based approach.

- Re-use of manufacturing equipment through requirement engineering.

A connection between the decision support tool with the requirement engineering domain would increase the confidence to use smart technology in production systems. The finding is a result of strategic considerations pointed out by the technology experts to reduce the risk of failures by increasing the re-use of purchased equipment. In case of an unsuccessful attempt of automation, the equipment could be reconfigured and used in a different production context. Therefore, the framework considers requirement engineering.

4.2.3 Framework Design Requirements

The arising implications can be merged into a list of requirements for the decision-support framework. The underlying assertion is that an early-stage decision support framework is required. The limited information with regards to the system design can be supported by extracting functional (technical) requirements for the intelligent automation system. The human factor domain has accumulated significant knowledge to date about important task information. But, at the point in writing, the actual systematic translation of functional data derived from a human task into technical information is hardly addressed. The decision support framework should provide a reasonable answer to the identified issue as the basis for the later decision process. An ideal solution would be one that is *easy to use*, *aids the analysts' or decision-makers' task*, and *systematically provides important task information for automation*. From a process representation and modelling perspective, the collected information should lead to the creation of functional entities allowing the differentiation between levels of automation (LoA) and representing a technical view on the functional requirements. The process model should further allow the transfer of required constraints related to the layout, structural task dependencies, and/or schedule dependencies.

The scarcity of historical or design information leads to a complexity increase in the decision mechanism due to an increase in uncertainty. The uncertainty must be modelled accordingly. Different mechanisms have been presented thus far. The assessment must consider the identified functions. However, an evaluation should not be based on a consideration of cost data and introduce a practical approach to decision-making with a technical perspective. Due to the sensitivity and novelty of the research environment, no historical information is available to base the decision on. Hence, an assessment must be based on the modelling of expert knowledge.

The implications derived from the literature review (Chapter 2) and the extended studies (Section 4.1) serve as a justification for the structure of the presented framework.

4.3 Conceptual Framework

This section introduces the conceptual framework of the thesis with regards to the identified research gap and in the literary context. The following sub-section will review the information that is required iteratively to enable the decision-making process.

4.3.1 Framework Information Flow

The conceptual framework is informed by three information sources. The three different sources that inform the conceptual framework are the task analysis and human factor domain, the process representation domain, as well as the decision-making for the automation domain. Subsequently, the framework is divided into three information stages as according to the identified domains. The following figure presents an overview of the current established requirements and information determining the decision support framework.

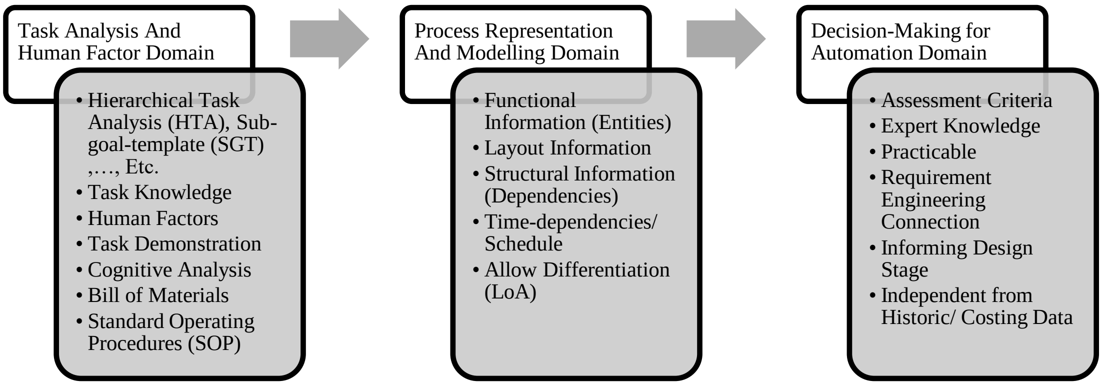


Figure 4-2: Structural Information Diagram for Conceptual Framework.

The task analysis and human factor domain represent the information currently available for the manual process. Based on different tools (for example HTA or SGT), the information density might be increased. Additionally, the existing process documentation provides the technical detail of the production process if required.

The collected information feeds into process representation and modelling domain. The information on the manual tasks should be used to created functional entities within the created model. The entities are structured in a specific way with regards to the current layout, functional entity dependencies and schedules in a way allowing a differentiation for levels of automation.

The decision-making domain requires information about the relevant assessment criteria, and expert knowledge to model the individual functional entity. The assessment of the functional entities should be easy to execute from a practical perspective. The created information should be connectable to a requirement engineering approach. The solution must demonstrate a logical connection to provide information in terms of the process design and product design stage for automation. Simultaneously, the required assessment information must be independent of the process and product design and focused on a probabilistic assessment rather than on cost data. The required transition processes will be presented in the following sub-section. Before the focus is on a detailed description of the framework parts, context to the framework arising from the decision environment will be introduced.

4.3.2 Decision System

The conceptual decision system consists of three sub-systems describing the *decision environment*, *the early-stage decision framework*, and the *connection to* later stages of the *automation-decision process*. Within the early-stage decision framework, a detailed distinction between the task analysis and human factor domain, the process representation and modelling domain, as well as the decision-making for the automation domain has been presented following the information flow. The following parts introduce the decision-support framework and the environment more detailed. A graphical framework overview is presented in Figure 4-3. The first subsystem presented from the decision system is the decision environment.

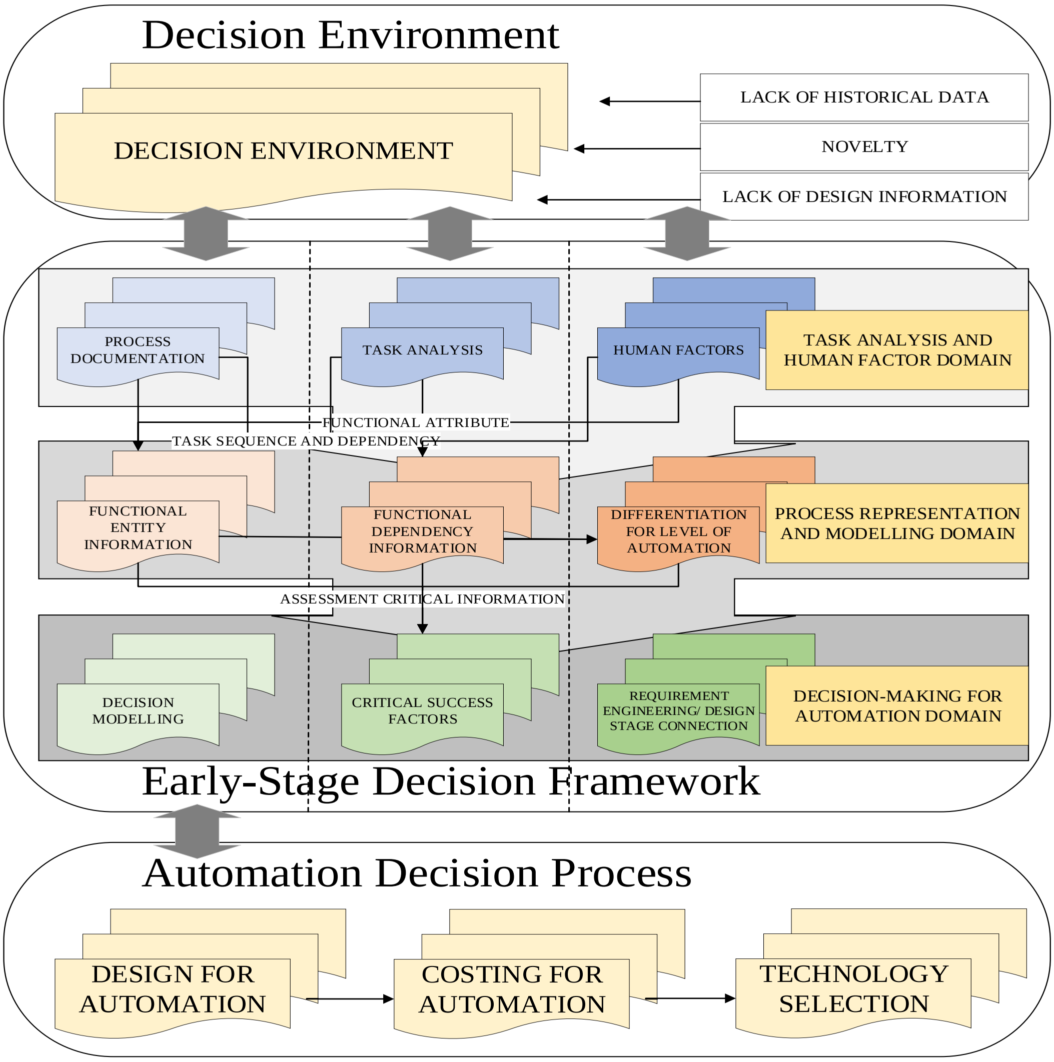


Figure 4-3: Decision System

A. Decision Environment

Due to previous decisions, the environment I s confronted with several limitations. The mentioned limitations are a *scarcity of historical data* (sensitive business information and lack of intelligent automation cases), *novelty* (uncertainty due to the early stage), and a *lack of design information* (early-stage decision prior to system design stage).

The lack of historical data is caused by its connection to sensitive business information in combination with a limitation of cases available for intelligent automation. Automating the process is directly related to a generated *competitive advantage*. Even if a company had introduced intelligent automation, the business would be retrospectively *reluctant to disclose relevant information for other businesses*. The second factor identified as a direct influence is the novelty created from a shortage of existing data. Since the decision must be based on the manual task analysis, each individual operator performance leads to a unique task. The *effect* of such a *novelty can be reduced by choosing the right process level for a manual task abstraction*. The last factor is related to the timing of the decision-making process. *Limited design information* is caused by the *timing prior to the design for automation stage*. The *factor reduces the possibility to conduct similarity studies* with existing systems.

Since database approaches can consequently be excluded from the list of options for the decision-modelling, a limited number of options remain. As a consequence, the identified decision environment leaves only expert elicitation and expert-based decision-making as an option for the decision-making process. The subsequent chapter introduces the main subsystem, called early-stage decision framework, as central part of the decision system and corresponding to the environmental subsystem as well as later decision stages.

B. Decision Framework

The subsystem "early-stage decision framework" consists of multiple domains. The domains have been mentioned previously and are referred to as the *task analysis and human factor domain, the process representation and modelling domain, as well as the decision-making domain.* The central reason for this separation of areas was the information stage. The first part of the framework is the task analysis and human factor domain. The domain is informed by the *process documentation*, the *task analysis*, and *human factors*.

a. *Task Analysis and Human Factor Domain*

The process documentation relates to information obtainable from internal documents that provide technical information about the manual production process. Examples of such documents are Standard Operating Procedures (SOPs) or technical drawings allowing the later process representation and modelling domain to obtain specific details of the process/task/operation (for example tolerances). The task analysis domain relates to the current procedures of a task analysis like, for example, the HTA or the Sub-Goal-Template (SGT). The task analysis commonly provides a chronological structure of the production process performed by one or multiple operators. The human factor domain deals with soft factors related to the human task. The technical and manual process structure can be extended with additional detail as a result of different human factor analysis models. Those models can be used to add detail to the automation consideration (for example ergonomics or mental strain). The aggregated knowledge must be used to condense the uncertainty of the process design by adding information to the process representation and modelling domain.

b. *Process Representation and Modelling Domain*

Generally, the process representation and modelling domain contain four different areas represented in the literature review (see Section 2.2). The four identified areas are *production information, production layout, production scheduling,* and *optimisation*. The framework has adopted the view apart from optimisation. *Functional entity information* contains information about the individual functional entity. A functional entity is the smallest set of specific activities natural to or the purpose of a process, working in a particular way. The *functional entity* must be created by a *fusion* of *process documentation, task analysis* and *human factor knowledge*. The fusion of task knowledge must consider key attributes for the decision-making process. An *attribute* represents a *characteristic of* the *manual manufacturing process key to the functional abstraction* for decision-making purposes (for instance the underlying purpose). In the literature review (Chapter 2), *artificial intelligence-based models* have been presented to *model uncertainty* based on the extraction of *dataset characteristics* through *similarities*. *Clustering algorithms* represent a *search heuristic* for an *optimal selection based on data similarity*. Using such an algorithm might be useful to approximate similarities among manufacturing tasks.

The layout and scheduling knowledge are represented by extensive information about the task- interdependencies obtained from the task analysis and human factor domain. The information is crucial for the creation of functional entities as relationships among tasks are described. An example shall be a grinding/polishing process. Manual grinding and polishing are achieved by many iterations decreasing the grain size over time/iteration. In the present case, a process with such similar characteristics might be generalised in the same functional entity. However, the real application might be represented by a sequence of similar operations. The additional information must be used to prevent an accumulation of similar activities where unintended. In addition to the generic process modelling parts, the process representation needs sufficient depth and granularity of attributes to enable considerations of different LoA. A combination of those three modelling parts is the basis of the decision-making process.

c. *Decision-Making for Automation Domain*

The decision-making information stage of the framework consists of three constituent parts. The three parts are *decision modelling, critical factor assessment,* and *a requirement engineering and design stage connection.* The basis for the early-stage decision-making framework has been established by a functional representation of the manual manufacturing task. The functional entity and dependency information in combination with enough depth and granularity to defer between different functions, with respect to the level of automation, lead to the assessment stage. According to the framework requirements, the functional description must enable a technical perspective for the automation assessment. Before the assessment takes place, a decision model must be created. The *model depends* on the *decision environment*. In the literature review, specific ways to model uncertainties have been presented. The decision environment is characterised by a *scarcity of historical data* and a *lack of design information* as well as *novelty*. The novelty and lack of design information can be mitigated via functional decomposition of the manual task. A *remaining problem* is the *lack of historical data*. A lack of historical data *limits* the *decision-making* to an *expert-based model*. Expert knowledge modelling or expert systems create a knowledge database to inform the decision process.

A *formalised way* of expert knowledge extraction is *expert elicitation*. Consequently, an *expert elicitation* must take place to inform the *critical success factor assessment* part. An understanding has been developed that the automation decision is influenced by a large number of decision variables. Based on the accumulated knowledge, a decision was formed to *conduct a probabilistic assessment via expert elicitation* (see section 2.3.5). Since numerous variables and interdependencies would have to be considered, *remaining uncertainties* must be additionally modelled. To reduce the probabilistic uncertainty, a simulation approach can *extend* the *expert elicitation dataset* to *model* the *interference, correlation* and *interdependencies among decision variables*. The established automation decision should relate to the overall automation decision context. The following sub-section will describe how a connection between the decision-making process and the *design for automation* stage is achieved.

C. Automation Decision Process

The decision-making process takes a technical perspective on the automation decision. The perspective requirement should model the manual process and ensure a setup in a technical context. Ideally, *critical success factors correspond* with *the functional structure of the human process, which means that the right generalisation approach has been taken for the operations*. The correspondence can be used to identify factors currently problematic to the intelligent automation process. Individual identification of factors might lead to an understanding where a structural improvement to the process or product enables/improves future automation. The functional structure enables a connection to requirement engineering approaches in the future (but this is outside the scope of this research).

4.4 Framework Summary

The conceptual framework presented in the chapter leads to the realisation of the model enabling tests on real case scenarios. As previously pointed out in the methodology section 3.2.1, historic case studies have been selected to validate the model rather than new case studies, where a current decision cannot be validated. The downside of the approach is that business information must be based on assumptions, which poses the risk of a biased interpretation of results. However, the assumptions will be presented and explained transparently in the results section. Before the case studies are assessed, however, the framework must be transformed in detail into a decision support tool, which will enable the application and validation of the framework.

5 Early-Stage Decision Tool

“Man is a tool-using animal. Without tools he is nothing, with tools he is all.” – Thomas Carlyle

This chapter explains the development of the early-stage decision support tool based on the conceptual framework. A computer-aided tool is needed to support the implemtation of the conceptual framework due to complex calculations, data processing, and database reasons. This chapter consists of three parts. Section 5.1 explains the methods applied to develop the tool. Section 5.2 describes the mathematical relations of the framework. The realisation demonstrates an attempt to concretise the conceptual framework in a real-world environment. The mathematical realisation leads to the development of the early-stage decision-support tool for intelligent automation. Section 5.3 describes the Microsoft excel demonstrator toolbox. A more detailed view of the tool can be found in Appendix D, where the tool and the applied algorithms are depicted in detail.

5.1 Justification of Methods for Toolbox

To validate the established decision-support framework, a toolbox must be created to test the framework via multiple case studies. The following sub-section introduces the selected case studies and explains the reason for the selection. After the justification of the case studies, a justification of the methods and the course of the tool development will be explained.

5.1.1 Case Studies (Justification of Historic Case Studies)

Two different alternatives were considered. The two alternatives are either to use live intelligent automation projects or to use historical case studies. Live case studies have the disadvantage of unavailable outcome information, historic case studies are restricted in terms of available information to determine decision-factors. For the evaluation of the decision support tool, a decision was made to use historic case studies were the automation outcome is known. The decision enables a comparison between the established and the real scenario. However, a limitation to the approach is that assumptions must be made where historical data cannot be obtained. All studies were recorded and prepared via a hierarchical task analysis and an IDEF0 process as currently used for the manual task analysis of production processes [38]. The case studies were analysed recording specific production processes for automation purposes. A detailed decomposition structure of tasks can be found in chapter 5. The evaluated case studies are collected from the ESPRC Centre for Innovative Manufacturing in Intelligent Automation[4] and build the foundation of the intelligent automation project evaluation. The selection of case studies represents a variety of manufacturing processes (see Table 5-1).

Table 5-1: Case Studies

Case Study	*Description*	*DIN 8580*	*Main Investigator*
Welding	Adaptive TIG Welding, Vacuum Bag TIG Welding	Joining Through Welding	Dobrzanski, Sanchez-Salas [141]
Grinding	Grinding and Polishing of Complex- Shaped Surfaces	Cutting with geometrically undefined cutting edges.	Kalt [230], [231]
Beater Winding	Production Process of Beater for Music Instruments	Textile joining	Zhao [39]
Threaded Fastener Assembly	Automated Freeform Assembly of Threaded Fasteners	Assembly	Dharmaraj [232]
Deburring	Removing defects/ burrs from manufactured parts.	Cutting with geometrically undefined cutting edges	Sanchez-Salas [141]

A more detailed description of the cases studies can be found in the cited literature of Table 5-1 , summaries are also included in Appendix B. The case study welding has been selected to demonstrate the functions of the tool in this chapter. In-depth information on the selected case study can be found in Appendix A and Appendix B. Relevant information will be displayed throughout the following sections. The following sub-section introduces the justification of the methods used for the systematic representation of early-stage information.

5.1.2 Systematic Representation of Early-Stage Information

Ways to bridge the gap between the manual task abstraction and the automation decision-making were examined for the realisation. The aim of the functional representation had

[4] Research Grant can be found under: https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/I033467/1, last visited on the 19th of March 2019, 11.50 am.

to satisfy multiple objectives as arising from the literature review (chapter 2). The analysis of a complex structure might face difficulties due to the task variables nested within one another as part of a continuous production process. However, before the synthesis of information can be performed, attributes must be discovered to identify process functions as according to current risk-assessment approaches. Despite the available standards and research to date, systematic identification of process functions appears to be unsolved in the current context. Examinations must be conducted to establish a classification for the physical, perceptional, and cognitive tasks.

To enable a process decomposition based on attributes, the method must extract the different functions from the available information. To achieve the goal, three challenges must be addressed. The first challenge is the attribution of the manual process. As part of the second challenge, an update of the existing classification scheme must be made. To create a functional task abstraction, the existing standards must be extended through the development of a tactile and visual perception framework identifying main perception functions. The last remaining challenge is how to link the manual process to the actual classification scheme. A many-to-many relationship was chosen for one task entity to belong to multiple manufacturing attributes as well as one manufacturing attributes to belong to multiple task entities. The relationship type of both entities (manufacturing function, task) is, hereby, defined as a binary relationship. The classification allows the user to rate whether the manufacturing process shows attributes related to a specific manufacturing function. However, is worth to be mentioned that the right level of task entity attribution was unclear at the specific point in time and had to be investigated. After the classification using binary attributes, the systematic synthesis of the information could be addressed.

5.1.3 Synthesis of Information for Decision-Making Process

For the realization of an information synthesis to create task functions based on underlying patterns in a data set, a clustering algorithm has been chosen. Clustering is an approach widely used in applications extracting patterns in the underlying database. After receiving a detailed structure of the tasks and developing a classification scheme in the previous section, the second part (clustering) is approached. Clustering is a logical transition step to abstract attribute dependencies among the manufacturing process. The aim is to identify a structure based on the attribute similarities of the production processes. The algorithm extracts the classification data from the process. The identified pattern describes a connection between different operations and attributes (later found to be the most appropriate attribution level). Most of the common clustering algorithms are excellent for handling data sets with continuous data. And yet, categorical data is frequently an issue in the real world for clustering problems. Therefore, a robust algorithm was chosen capable of handling categorical data (incl. binary data). The chosen clustering algorithm is a modified k-means clustering algorithm.

Before the cluster analysis starts, however, the process operations had to be manually attributed using the established classification scheme. Additionally, time relationships among the identified process functions must be considered. Ideally, the extracted process functions contain automation requirements, which allow the identification of corresponding automation equipment. A structured representation of automation-critical functions shall lead to a decision-making method.

5.1.4 Extracting Critical Decision Factors

For the determination of critical decision factors, the experts' opinions about critical decision factors and their relations are abstracted using the DELPHI- method. The decision was inspired by the literature review suggesting a reduction of error sources via a structured expert elicitation. At the early stage of the decision process, only limited useful information (initial manufacturing process and the standard operating procedure) is provided. Therefore, the expert elicitation and modelling must build upon the previous work. Earlier, the manual processes were attributed, sorted into functional components (clustering), and the sequence variable for the individual operations determined. The last step of the framework is supporting the intelligent automation decision based on structured knowledge.

The depth of the required information forces the researcher and respondents to talk about the same system setup. The attendants must understand what the question/answer contextually means, limiting the methodology to an expert workshop. The workshop is used to gain a consolidated view on the decision factors and the relationship (DELPHI method). Thereby, the group is divided into subgroups and iteratively merged into bigger groups with a discussion of presented results to generate a consolidated view. A survey might lead to a misunderstanding of the questions allowing unguided thinking and imagination of the decision process. An expert interview might focus too much on the individual expert and makes consolidation of knowledge subject to interpretation. The results of the expert workshops are applied to create a relationship-network for the future evaluation of cases based on the experts' opinion. On top of the created network, the experts are now interviewed in one-on-one sessions about the prior probabilistic dependencies of parent and child nodes. Bayesian networks (BN) are chosen as a method in the area of risk and reliability modelling (see for example [233]). Several reasons are given credit for that:

- A lack of historical data to use database-driven methods like reinforcement learning or neural networks,
- high complexity does not allow to apply logic approaches,
- BN enable causal reasoning among factors,
- expert system for decision-making,
- and knowledge updatable.

5.1.5 Decision Modelling

Bayesian networks are part of probabilistic graphical models using the graphical structures to represent expert knowledge based on statistical/probabilistic data [234]. Due to the fact, that historical risk data for automation is limited and, therefore, found insufficient for solid statistical analysis, the probability distribution of a set of critical success factors is extracted using expert knowledge. Bayesian networks that represent expert opinions are called Bayesian Belief Networks (BBN). The complexity of the problems occurring, especially with regards to intervariable-dependencies and the resulting influences, might be underestimated. A glance at Figure 5-1 reveals an increasing complexity for every added critical success factor (in the depicted case, only the last nodes are connected). The presented factors are binary (True and False). In a more complex BBN, the values of the critical success factors could be distributed over a range of categorical values (for example, blue/red/yellow or high/medium/low). Therefore, extracting detailed expert knowledge of every interference of the nodes (critical success factors and their categories) as well as the occurring combinations is impractical. Asking an expert about every possible interference would require over 100 additional questions to determine the occurring influences for the given example. Neglecting intervariable-influences, on the other hand, might have a significant impact on the results. BBNs aim to model such complexities, where probabilities depend on another.

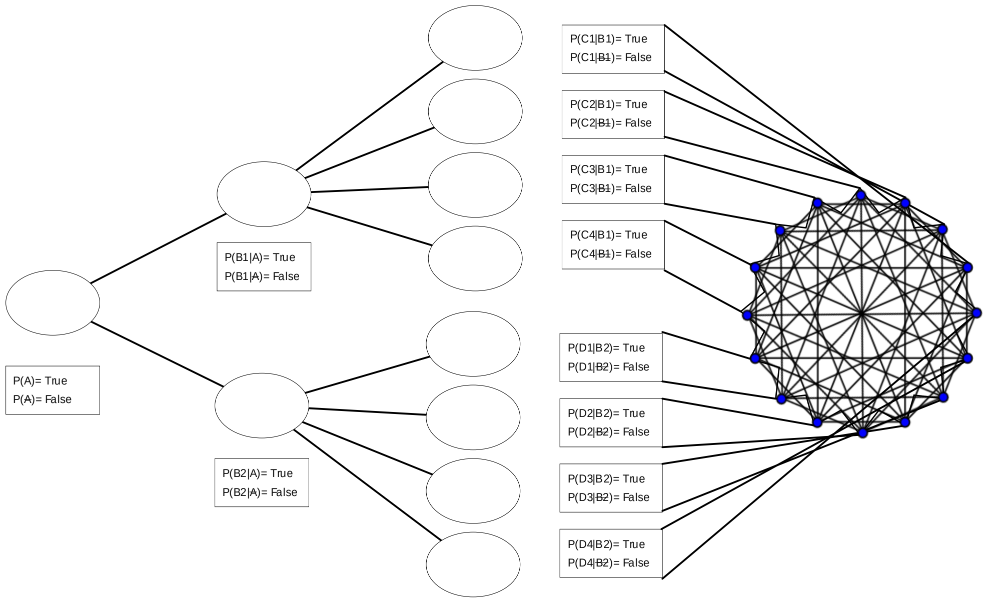


Figure 5-1: Bayesian Belief Networks for Expert Knowledge Elicitation - Complexity Model.

More clearly, one specific critical success factor is expressed through a chain of posterior probabilities. A posterior probability is the conditional probability given to a specific event after the relevant information/evidence is taken into consideration. The word posterior means that the examination of the probability is based on the previously given information. The process is repeated for every consecutive node within the BBN until the last level has been reached.

However, the construction of a BBN is a trade-off. Since two factors might not be independent, or partially independent or dependent, the influence of a specific factorial combination cannot be easily obtained. Based on the prior distribution, only the effect of one factor can be calculated, not a combination of factors. And yet, dependency information is critical to mitigating related effects on the outcome. Specifically developed algorithms have been invented to model factorial combinations. The algorithm should allow the researchers to be (i) sufficiently flexible to guarantee reasonable performance in the context, (ii) to draw quickly independent samples and (iii) to be calibrated with a reasonable effort using past simulations to conclude on the actual distribution over all factors.

Algorithms allowing such effect mitigation through artificial sampling are called importance sampling (IS) algorithms. A high number of different algorithms are available to date. A selection of important sampling algorithms frequently mentioned are:

- Adaptive Importance Sampling (AIS)
- Evidence Pre-Propagation Importance Sampling (EPIS)
- Likelihood (Weighting)
- Clustering
- Markov-Chain Monte Carlo

Controversial opinions suggest different algorithms as the best choice in terms of speed, effort and calibration. In the following approach, the dependency information is simulated via a Markov Chain Monte Carlo (MCMC) sampling algorithm. The main criteria are weighing up the ease of setup and the capabilities of the algorithms. The likelihood weighting sampling has been rejected due to criticism about the accuracy of the achieved solution. For later evaluation, however, the results of the chosen algorithm will be compared with a commercial tool using different sampling algorithms on one expert network to validate the applied mathematical model. Due to the time effort of comparison and the limited project time, only the first Bayesian Network will be validated. The mathematical modelling for the second network is identical.

5.1.6 Development of Decision-Making Tool

To validate the framework, the decision support tool must be developed using the created methods and integrating those methods in a specific toolbox. This part is displayed in section 6.3. Due to the preferences of the industrial partners, the choice has been limited to online tools or the creation of a Microsoft Excel © based decision support tool. Reasons are due to the companies' policies, which are limited in the permission to use tools from unknown/uncertified sources.

5.1.7 Validation of Early-Stage Decision Framework

The creation of the decision support tool allows the production of results using the collected case studies and a connected validation. First, the generated clustering solution is compared with IDEF0 solutions for validating purposes based on the collected case studies.

To validate the framework, case studies had to be collected to enable validation and verification of the developed decision-support framework in a practical context. After the validation of the functional abstraction, a framework established by Pitchfort and Mengersen is used for validation of the BBN [235].

A. Clustering Using IDEF0

As stated before, a comparison of the clustering algorithm with the IDEF0 solution from automation experts is intended to see whether an improvement of the current procedure can be achieved. The idea of using IDEF0 for process modelling is well established in the manufacturing area and currently lacks an alternative solution and systematic solution [12]. A similar approach for rating the automatability of manual tasks related to variability is presented by Sanchez-Salas (2016), who uses IDEF0, which is fed by the information of an HTA analysis to define different states of manual processes [7]. A functional abstraction must meet the IDEF0 at a level to compare the clustering solution with the expert-based IDEF0 model.

The comparison will serve to see how suitable the presented solution is for automation decision-making and whether the solution provides a basis for future research to build upon. Every single identified cluster will consequently be presented as a specific function. IDEF0 as an instrument is the representation of processes, which are ordered as a set of functions. Those functions are carried out in a determined and standardised way [236]. A function is “a set of activities that take certain inputs and, by means of some mechanism, and subject to certain controls, transforms the inputs into outputs”[236]. A starting point is the setup of the system in its environment to define the systems’ aims and interfaces with the environment. Within the context diagrams, the system contains a hierarchical and chronological structure of related diagrams decomposed at a lower system level to enable both, a wider and broader perspective [236]. Similar to the first model reducing the design information uncertainty, the decision-model has to be validated to reduce the uncertainty related to available information.

B. Business Cases

To assess the BBN in a fair and independent manner, the thesis has subjected itself to the restrictions of a Validity Testing Framework for Bayesian Belief Networks based on

Pitchforth and Mengersen [235]. The key criteria of the selected framework are a validation of the following main aspects of a Bayesian Network:

i. Nomological Validity and Face Validity
ii. Content, Concurrent, and Convergent Validity
iii. Discriminant Validity
iv. Predictive Validity

A more detailed description can be found in chapter 6. Based on the evaluation and validation of both, the clustering and the feasibility network, a reflection on the decision-support tool and drawing conclusions will be enabled.

5.2 Tool Design

This section describes the design of the decision support tool. As defined in chapter 4, the starting point of the framework is the task analysis and human factor domain. Knowledge gained from an extensive task analysis allows the development of a classification to attribute operations with the right granularity. Based on the classification scheme and tasks containing allocated attributes, a clustering algorithm is chosen to structurally identify task functions. The task functions allow a user-based allocation of automation functions. The functions are then used for an expert-based elicitation.

The following Figure 5-2 depicts the tool design and the underlying relationships to give a graphical overview of the following chapter. The starting point is the task analysis and human factor domain. Structure task information is converted into a process function. The individual process functions can eventually be used to evaluate the task for automation.

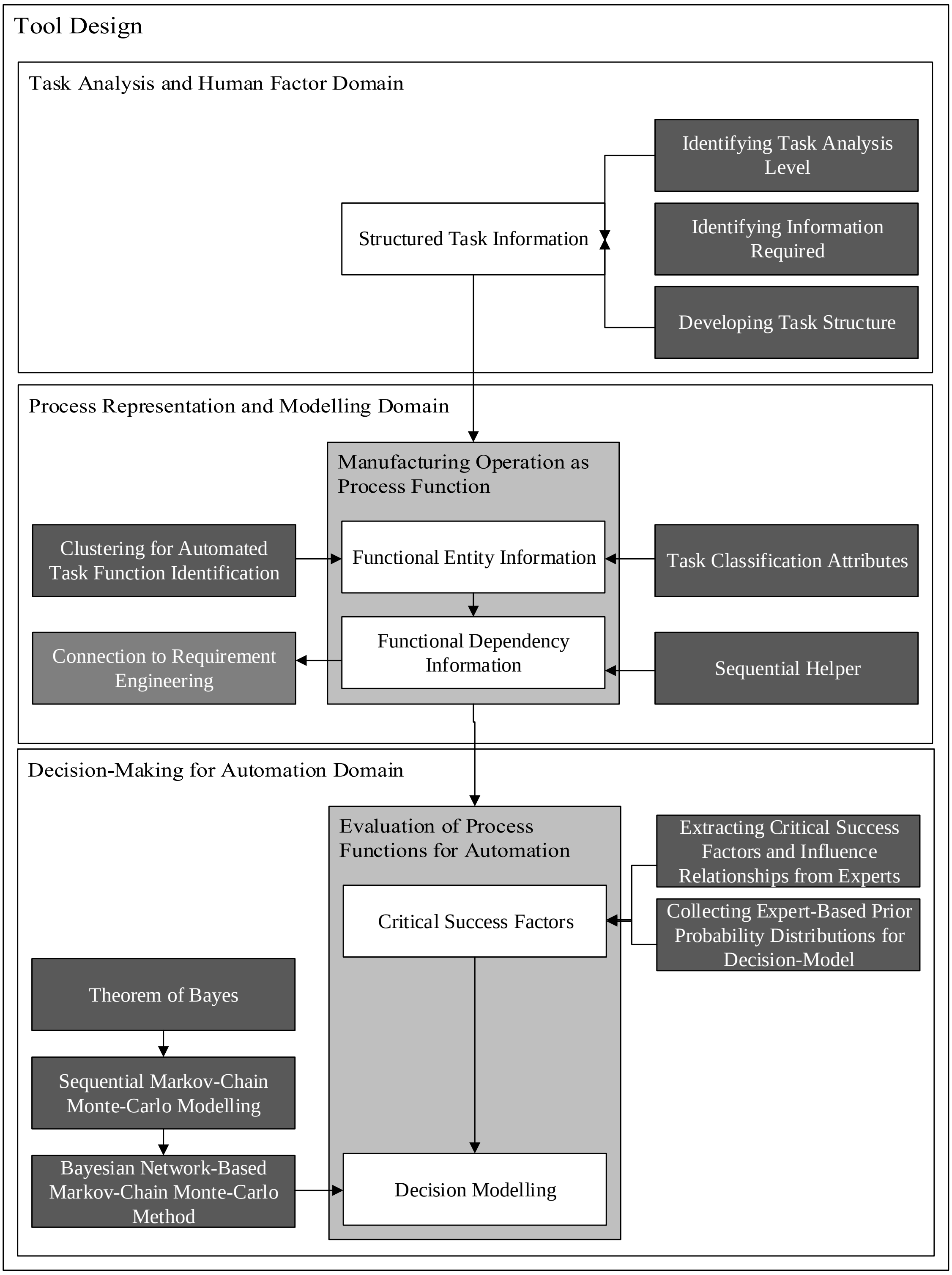


Figure 5-2: Overview of Tool Design and Relationships.

5.2.1 Task Analysis and Human Factor Domain

This section describes the adoption of knowledge currently used in the task analysis domain and the way the knowledge was extended to create the desired outcome of systematic functional task abstraction.

In this research, multiple methods currently used for the decomposition of human tasks are combined. The need for human task and factor considerations has been identified in section 1.3.1, where researchers pointed out problems related to automation projects in the absence of human factor considerations. The initial input to the proposed approach is a hierarchical task analysis (HTA) extended with a sub-goal template (SGT) study to represent actions contained in an individual operation. The task is decomposed into operations performed during the manufacturing process. The hierarchical level description (see Figure 5-3) is adapted from Lohse [311]. Lohse separates a manufacturing process into different tasks, which are subsequently divided into manufacturing operations. The manufacturing operations can be split into a sequence of actions. In the data structure, the manufacturing actions are represented by the SGT method.

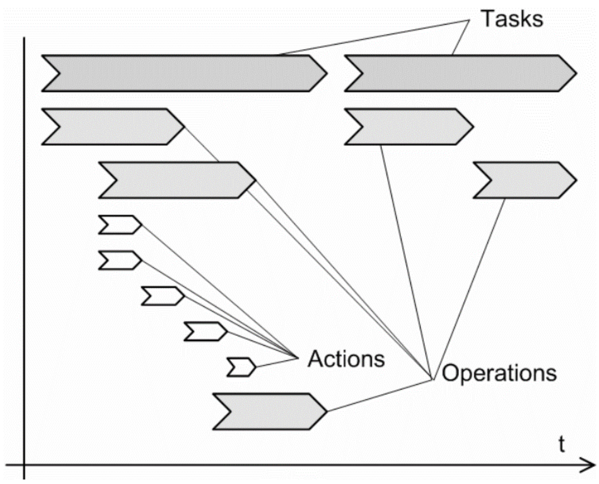


Figure 5-3: Activity Hierarchy Definition adapted from Lohse [311].

The operations are sorted with respect to time in a chronological manner starting with the first task. The data structure established for the operation analysis is shown in Figure 5-4, based on a defined operation decomposition structure. The hierarchical task structure of different case studies is used initially and extended to include the different SGT elements based on Ormerod et al. [42]. Every operation is labelled with a name and a specific sequential ID. The operation contains not only physical actions but also cognitive actions performed during the manufacturing process. The cognitive activity is related to the object or the tool, whereas the physical activity is related to specific multiple body parts.

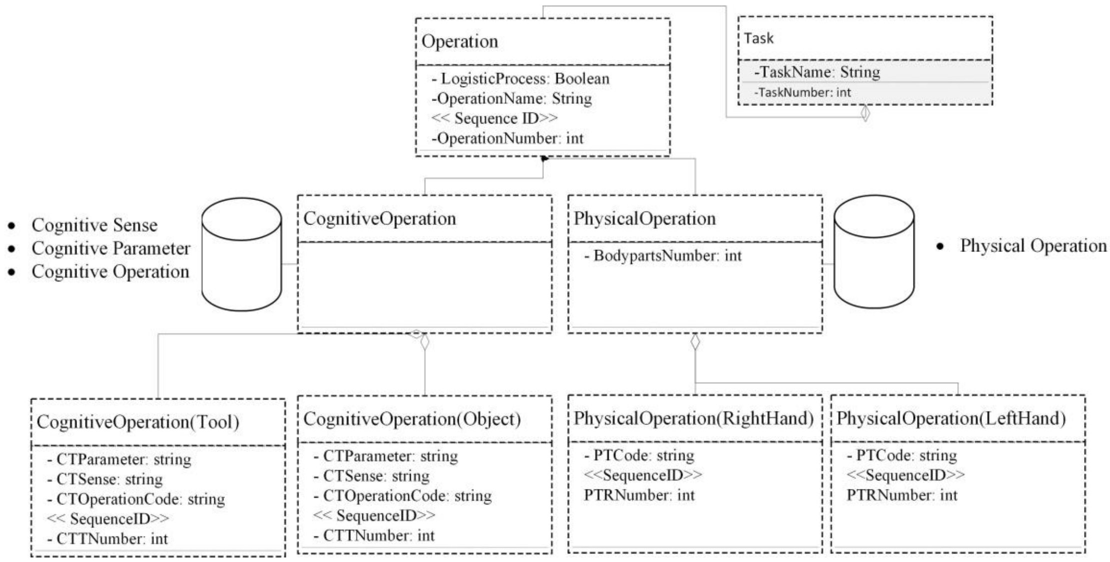


Figure 5-4: Extended HTA Data Structure for Operation Analysis.

The in-depth analysis of the created task-operation-action description (see section 6.1), however, has led to a different conclusion for the realisation of the conceptual framework for the following reason:

Despite the detail provided by the SGT and the justification for using the approach for different purposes, in the decision-making context the description was found to be too detailed. The approach did not allow a suitable attribution process at that level of detail since an operator performs a sequence of actions different from an operation the automated system would perform. On an action level, the worker even performs actions in different ways. An example is 'Grind tip of the electrode'. For the automation system, the approach could be fully automated using a standardized automated grinding process, the worker must perform a sequence of actions that lead to the same result. However, within this sequence, even similar working processes are executed differently on an action level. Such a sequence would be grasping, adjusting the position, switch on the abrasive belt, etc. until the result has been achieved. On top of that, the level of detail increased the difficulty to reproduce the results and the development of an SGT task structure was recognised as very time consuming for early-stage decision support.

The conclusion drawn from the applied task structure of Figure 5-4 is that the task decomposition should take place on a level above the action level – the operational level. The detailed justification can be found in the result section 6.1. Purposefully, the following work was adopted to the initial findings. For brevity, the presented example in Table 5-2 displays only a subset of the task analysis for the welding case study (one of the 5 case studies) on an operational level. The full set can be found in Appendix A.

Table 5-2: HTA Example - Welding Case Study (see Appendix A and B)

HTA Level	*Process Level*
1.1 Select filler rod	[task] with 1 [operation]
1.2.1 Select electrode	[operation]
1.2.2 Grind tip ofthe electrode	[operation]
1.2.3 Select collet and ceramic nozzle	[operation]
…	…
2.4 Hold filler rod in left hand	[task] with 1 [operation]
2.6 Adjust equipment position	[task] with 1 [operation]
2.7 Remove objects impeding movement	[task] with 1 [operation]
…	…

For the future realisation process of the conceptual framework, the manufacturing task will be investigated on an operational level. Based on the determination of the right task analysis level, the process representation and modelling domain can be informed.

5.2.2 Process Representation and Modelling Domain

This section presents the realisation of concepts in the process representation and modelling domain. In the conceptual decision-framework, the domain was separated into three critical elements for the process representation and model. The first critical element was functional entity information.

A. Functional Entity Information

The creation of a functional entity in the conceptual model has been derived from a fusion of task analysis and human factor domain knowledge. The transition process suggested using attributes representing key characteristics of the manual task. The previous section found that the right level for task attribution is the operational level to achieve the maximum detail. A possible solution was driven by the idea to use a search algorithm to detect attribute patterns among the dataset to combine similar operations into functional clusters. Therefore, clustering was identified as a possible solution to create task functions based on a human operation analysis. Rather than using the hierarchical task information to form manufacturing functions, the functions will be created individually as according to the actual attribute an operation performs. This way, a separation between human performance and the task function can be achieved to overcome the problem of dissimilarities between human and automation operations. The necessary requirement to enable clustering is a task database containing critical decision attributes of the sample. A classification scheme based on existing standards and the existing literature is used to attribute the process tasks. The developed classification scheme is presented in the following section.

a. Classification Scheme

The development of a classification scheme is to identify existing process classifications to enable a structured separation of manufacturing operations through attribution. The classification scheme provided by DIN8580 standard, which is (numerically) followed by other more specific standards was selected. The table presents a small selection of the classification based on the DIN8580 and related standards (see Table 5-3).

Table 5-3: Selection of classification categories based on standards around DIN8580

Attribute Description	*Attributes assigned in Eq.1*	*(Sub-)Standard and References*
Changing material characteristics through particle transfer	$a_1 = \{0,1\}$	[DIN8580]
…	…	…
Coating from a gaseous or vaporous state	$a_4 = \{0,1\}$	[DIN8580]
…	…	…
Placing	$a_8 = \{0,1\}$	[DIN 8593]
Filling	$a_9 = \{0,1\}$	[DIN 8593]
…	…	…
Textile Joining	$a_{16} = \{0,1\}$	[DIN 8593]
…	…	…

The presentation of those standards is used as an example for the reader to understand the idea behind the task/operation classification. For a comprehensive view, the classification standards are displayed in Appendix C. The application categories *represent sub-levels the manufacturing main categories joining, forming, etc presented in DIN 8580.* The presented manufacturing classification considers physical manufacturing operations only. Supporting operations related to the perception mechanisms (visual perception, haptic feedback) are not covered in the related classification. Hence, the existing manufacturing classification standards have been extended by different perception mechanisms. The full list of attributes can be found in the appendix C. A combination of research by Groover [312] with Lederman et al. [313] informs the classification scheme. The first adapted part by Groover presents a categorisation of visual perception mechanisms for robotic automation. The second incorporated research by Lederman et al. focuses on the tactile perception of humans. In accordance with their findings, a classification extension containing multiple perception attributes for a specific operation has been added. The result is a combination of tactile and visual perception senses as a decision criterion to identify the required sensorial requirements (see Figure 5-5). The figure has been developed according to the literature. The first step was an examination of human perception behaviour. Based on this behaviour, the author reasoned about abstracted parameters, which can be identified using a specific automated mechanism. In this thesis, rather than focusing on the automated mechanism, the parameters were derived into attributes for perceptional processes. Examples of resulting operation attributes would be *Visual Perception Object Shape* or *Tactile Perception Temperature.*

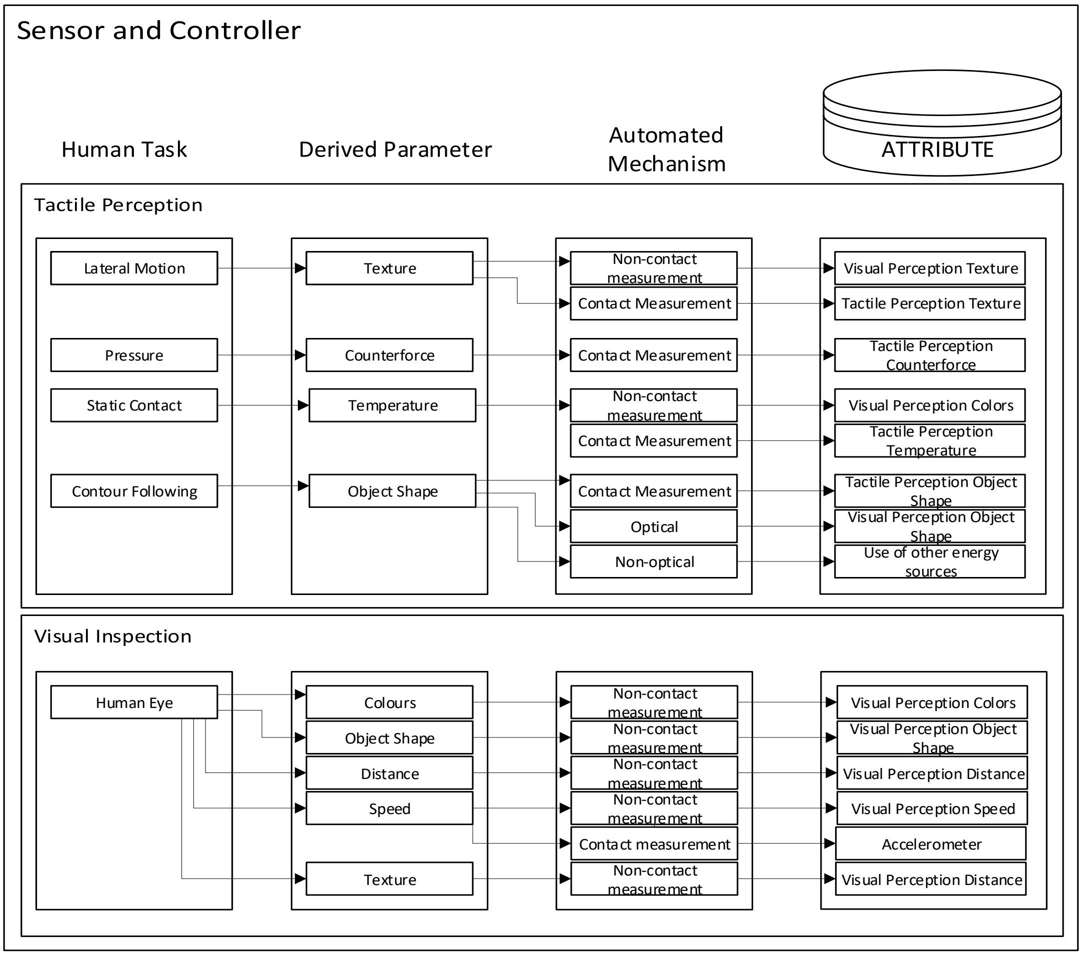


Figure 5-5: Tactile and Visual Perception Senses as Extension for DIN8580

The full list of classification attributes can be found in Appendix C.

b. Clustering for Automated Function Identification

The manufacturing classification against the operation is modelled as a many-to-many relationship expressed by a binary variable. In such a way, one operation can have multiple attributes and one attribute can be logically connected to multiple operations. As a consequence, the database is created. The user will identify attributes to every single operation as depicted Figure 5-6. The user will enter as many different attributes to the manufacturing operations as required. Every operation must be fully determined with the physical and perception attributes available in the classification scheme. One operation can require multiple attributes for an operation. An example is a welding process performed by an operator. In reality, the welding process is not just determined by an attribute responsible for the actual welding, but also requires human feedback to control the operation.

Process Name	Process Step #	Joining through welding	Cutting with geometrically	Pick And Place	Auxillary Operation	Assembly	Visual Inspection
1.1 Select filler rod	1	0	0	0	1	0	0
1.2.1 Select electrode	2	0	0	0	1	0	0
1.2.2 Grind tip of the electrode	3	0	1	0	1	0	0
1.2.3 Select collet and ceramic no	4	0	0	0	1	0	0
1.2.4 Assemble torch	5	0	0	0	1	1	0
1.3.1 Cleaning	6	0	0	0	1	0	0
1.3.2.1 Place based on holder on b	7	0	0	1	1	0	0
1.3.2.2 Attach gas supply	8	0	0	0	1	1	0
1.3.2.3 Secure welding piece	9	0	0	0	1	1	0
2.1 Place foot on foot pedal, and d	10	0	0	0	1	0	0
2.2 Put on gloves	11	0	0	0	1	0	0
2.3 Hold torch in right hand using	12	0	0	0	1	0	0
2.4 Hold filler rod in left hand	13	0	0	0	1	0	0
2.5 Move torch and filler rod	14	1	0	0	0	0	0
2.6 Adjust equipment position	15	0	0	1	1	0	0
2.7 Remove objects impeding mov	16	0	0	1	1	0	0
3.1.1 Set and turn on power at the	17	1	0	0	0	0	0
3.1.2 Turn on gas at a the gas cyli	18	1	0	0	0	0	0
3.1.3 Put on welding mask (visor r	19	1	0	0	0	0	0
3.2.1 Position torch at tack locatio	20	1	0	0	0	0	0

Figure 5-6: Attribution Matrix for Human Task Analysis – Welding Example.

Based on the selected attributes, the clustering algorithm can be connected to the operations level of an HTA. The following part displays the mathematical relationships between the created table and the clustering algorithm. As mentioned before, for every operation i recorded via HTA analysis, the *process attribute* a_{ij} related to the *manufacturing classification attribute j* is represented as a binary value.

Process Attribute a_i

$$a_{i,j} \in \{0,1\} \quad (1)$$

The binary value expresses, whether the specific process step incorporates operations that fulfil the criteria/pattern of a specific distribution of attributes. The different operation attributes result in an attribute matrix A, which can be created due to the operation sequence:

Attribute Matrix A

$$A_{dim\,(i,j)} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,j} \\ \vdots & \ddots & \vdots \\ a_{i,1} & \cdots & a_{i,j} \end{bmatrix} \quad (2)$$

The sequential attributed operations are used by the clustering algorithm to determine the similarity of operations related to the distance measurement between certain clusters. The attribute matrix A represents the matrix of the analysed operations and will further be used for the abstraction process. The algorithm aims to divide i operations into k different clusters appending every observation (operation) to a cluster centre (so-called centroid) with the closest mean [314]. The closest mean is related to the distance of the contained clustering attributes from the centroid attributes. K-means clustering is considered difficult from a computational perspective, however, many algorithms convert quickly to an acceptable local optimum [315]. The generic K-means algorithm is presented in the literature as follows:

A set of observations (x_1, x_2, …, x_n) has an m-dimensional real vector. K-means clustering divides the n observations into k subsets S = {S_1, S_2, …, S_n} to minimise the sum of squared distances [314].

k-means Clustering Algorithm

$$\underset{s}{arg\ min} \sum_{i=1}^{k} \sum_{x \in S_i} ||x - \mu||^2 \quad (3)$$

Starting the k-mean clustering with randomised values limited only by the max/min sample value throughout every operation attribute is generally possible. The assumption at the current point is, that the patterns will translate into categorical data or attributes carrying binary values. In case the attribute values are all binary, the identity matrix $I_{j,n}$ can be used to represent the starting centroids for the clustering process to advance the centroid handling algorithm explained in detail in the following paragraph.

Centroid Matrix C

$$C_{dim\,(j,n)} = \begin{bmatrix} 1 & 0 & 0 & & \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & & \\ & \vdots & & \ddots & \vdots \\ & 0 & & \cdots & 1 \end{bmatrix} = I_{j,n} \qquad (4)$$

K-means minimises the distance between the centroids $c_{j,n}$ and the attribute matrix by manipulating the centroid matrix C to reduce the distance vector D_{opt} values over all distances. The following functions show a detailed description of the steps needed to achieve the aim (3).

Distance di,n

$$d_{i,k} = \left(\sum^{i}\left(a_{i,k} - c_k\right)^2\right)^{1/2} \qquad (5)$$

The distance matrix D can be expressed with the following equation:

Distance Matrix D

$$D = \begin{bmatrix} d_{1,1} & \cdots & d_{1,k} \\ \vdots & \ddots & \vdots \\ d_{i,1} & \cdots & d_{i,k} \end{bmatrix} \qquad (6)$$

Table 5-4 depicts an example of a distance matrix for the welding case study using 5 different centroids.

Table 5-4: Distance Matrix (k=5) – Example Welding

Distances	*d1*	*d2*	*d3*	*d4*	*d5*
Operation 1	1.4142	1.4142	1.4142	0*	1.4142
Operation 2	1.4142	1.4142	1.4142	0*	1.4142
Operation 3	1.4142	0*	1.4142	1.4142	1.4142
…	1.4142	1.4142	1.4142	0*	1.4142
…	1.4142	1.4142	1.4142	0*	1.4142
	1*	1	1	1	1
	1.4142	1.4142	0*	1.4142	1.4142
	1.4142	1.4142	1.4142	0*	1.4142
	1.7321	1.7321	1*	1.7321	1
	0*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	1.4142*	1.4142	1.4142	1.4142	1.4142
	1.4142	1.4142	0*	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
	1.4142*	1.4142	1.4142	1.4142	1.4142
	0*	1.4142	1.4142	1.4142	1.4142
…	0*	1.4142	1.4142	1.4142	1.4142
…	0*	1.4142	1.4142	1.4142	1.4142
Operation n	1.4142	1.4142	1.4142	1.4142	1.4142

The created distance matrix can now be optimised in a way, that the distances are being minimised for different sizes of k. The value k represents the number of different cluster-centres. The optimal solution creates a distance vector D_{opt} , which can be minimised using the sum of distances. The optimised distances in the previous table are marked by a symbol (*). The distance vector represents the smallest distance of every column distance ($d_{1,1}$, …, $d_{1,n}$) according to the following equation.

Minimum Distance min Dopt

$$min\, D_{opt} = \sum_{i=0}^{n} (\min_{1 \le n \le k} d_{i,k}) \tag{7}$$

The results of the equation are the minimum distances of different centroids. The table shows different accumulated differences for specific *k* (see Table 5-5). Five different centroids are used to cluster the existing sample. An increase of the cluster number *k* leads to an overrepresentation of centroids as the distances convert to zero. A comparison of the distances is an indication of the k-effectiveness. Once the distances are all zero for *k*, the centroids are purely a representation of all the single cases available (in terms of attribute distribution) and did not follow the goal of reducing the dimension of the operation.

Table 5-5: Minimum Distance Matrix – Welding Example

Minimum Distance	*Min2*	*Min3*	*Min4*	*Min5*	…	…	**Min n**
1.1 Select filler rod	1.4142	1.4142	0	0	…	0	0
1.2.1 Select electrode	1.4142	1.4142	0	0	…	0	0
1.2.2 Grind tip of theelectrode	0	0	0	0	…	0	0
…	1.4142	1.4142	0	0	…	0	0
…	1.4142	1.4142	0	0	…	0	0
…	1	1	1	1	…	1	0
…	1.4142	0	0	0	…	0	0
…	1.4142	1.4142	0	0	…	0	0
…	1.7321	1	1	1	…	1	0
…	0	0	0	0	…	0	0
…	0	0	0	0	…	0	0
…	0	0	0	0	…	0	0
…	0	0	0	0	…	0	0
…	0	0	0	0	…	0	0
…	1.4142	1.4142	1.4142	1.4142	…	0	0
…	1.4142	0	0	0	…	0	0
…	0	0	0	0	…	0	0
…	0	0	0	0	…	0	0
…	1.4142	1.4142	1.4142	1.4142	…	1.4142	0
…	…	…	…	….	…	…	…
SUM	**25.945**	**20.971**	**13.899**	**12.485**	…	**6.8284**	**0**

A possible solution to address the issue is a selection of an optimal *k* via an investigation of the distances between *min* D_{opt}. As the results show in the previous Table 5-5, the optimal distances can be summarised to understand how well a specific number of centroids *k* covers the attribute vectors of the created attribute matrix A. Two criteria should be respected for the evaluation of a suitable cluster number *k*:

- Firstly, *k* cannot be chosen in a way of allowing a trivial solution. A trivial solution means the selection k centroids whilst reproducing the operation dataset by combining equal attribute cases. Such an approach would not effectively reduce or cluster the operations but display all the different cases.
- Secondly, *k* should be pointing out the biggest 'jump' in the sum of optimal distances related to the chosen attribute matrix and cluster number *k*.

As can be seen in Table 5-5, the accumulated optimal distances decrease with a growing k. However, a rapid decrease of the optimised distance vector at a specific time is noticeable (see in the example, from d_{opt3} to d_{opt4}). The discussed step points to several clusters significantly reducing the distance to the dataset's attribute distribution. The centroids indicate the main characteristics of the dataset. Resultingly, the next step considers the biggest jump in the optimised solution. The Bayes Information Criterion (BIC) was modified to find a possible solution to the depicted problem.

Optimal cluster number k

$$k_t = \begin{cases} if\ k_t = \max\limits_{1 \le t \le n}(k_{t+1} - k_t), k_t = k_{opt} \\ else, \qquad\qquad\qquad\qquad k_t = k_{t+1} \end{cases} \tag{8}$$

The presented solution shows sufficient results for the determination of the functional task entity information. A combination of different reasons is responsible for that:

- Firstly, an HTA contains a specific number of operations far away from what is considered a large dataset in the data science community.
- Secondly, the attribute values are binary (a={0,1}) and, therefore, the created distances have similar dimensions.
- Thirdly, a limited number of different attributes are connected to an operation.

The combination reduces the number of cases in all dimensions of the dataset and the minimum distances significantly. For the case studies, the presented criterion was proven to deliver sufficient results as solutions. The results will be validated against the experts' solution in Chapter 6. In the example, the biggest jump occurs for a cluster size k =4. The number determines that *four sets with different attributes are the main characteristics to differ among the investigated operations.*

The determination of a specific *k*, representing the number of centroids, enables the allocation of specific attribute distributions to a specific cluster centre. *Each of the final centroids can be considered the final vector that represents the functional entity information.* Based on the distribution, a table can be created displaying the percental distribution of manufacturing attributes within the resulting clusters.

B. Functional Dependency Information

The previous part collected the functional entity information. Based on the functional task abstraction, the user can identify in which operation a specific set of manufacturing attributes has been allocated (see Table 5-6). Selecting the filler rod and selecting the electrode have been allocated to centroid 4, whereas grinding the tip of the electrode has been allocated to centroid 2. Specific operations of the HTA analysis are allocated to specific centroids. The conceptual framework chapter has presented a case in section 5.2.2., where a polishing/grinding process displayed similar characteristics throughout. As the attributes' list demonstrates, such a scenario is possible using the classification developed and applied in the previous sections. A variable called "Sequential Helper" is used to prevent such a scenario. Every operation additionally displays "Keep" as value for the sequential helper.

Table 5-6: Hierarchical Task Structure and Allocated Centroid - Welding Example.

HTA Structure	*Allocated Centroid*	*Sequential Helper*
1.1 Select filler rod	4	Keep
1.2.1 Select electrode	4	Keep
1.2.2 Grind tip ofthe electrode	2	Keep
1.2.3 Select collet and ceramicnozzle	4	Keep
…	…	…
2.4 Hold filler rod in left hand	1	Keep
2.6 Adjust equipment position	1	Keep
2.7 Remove objects impeding movement	3	Keep
…	…	…

The sequential variable helps to identify a sequential dependency among the functional task entities. Consequently, the user must determine whether the specific operation can be allocated in a specific cluster considering sequential criteria prior to a representation for the decision part of the framework. Therefore, the user is asked to answer for every process step, whether specific operations should be allocated in a stand-alone function due to sequential importance or whether the operations should be kept in the existing cluster ("Keep", see Table 5-6). If the user responds negatively, the operation will create a new independent process function. The step allows the tool later to show the final process function considering sequential constraints (see Chapter 6).

Table 5-7: Process Functions and Attribute Allocation - Welding Example.

Process Function	*Joining Through Welding*	*Cutting with geometrically undefined cutting edge*	*Pick and Place*	*Tool Changing and Setup*	*Visual Perception Texture*	*Visual Perception Distance*
1	100%	0%	0%	25%	100%	100%
2	0%	100%	0%	0%	0%	0%
3	0%	0%	100%	0%	0%	0%
4	0%	0%	0%	75%	0%	0%

For the early-stage decision framework, the generated process separation is considered sufficient for the next step of the framework. Nevertheless, the following section will demonstrate how the presented work might be transferable into a requirement engineering approach to inform the design for automation stage of the decision-making process.

C. Connection to Requirement Engineering

Figure 5-7 shows the individual process function contains specific manufacturing attributes. Accessing the information might enable the identification of an automation system based on the accumulated functional requirements (attributes). The automation system design might unfold as individual attributes pre-determine system requirements feeding the design for automation stage.

The data structure is displayed in Figure 5-7. Based on the abstraction of tasks/operations into task functions, the clustering algorithm has created a supporting structure for a user-based automation-component/system-mapping. A requirement engineering approach is presented for the following step.

In the database, every manufacturing attribute could have an allocated requirement code stored in the underlying database. Simultaneously, a second database stores previous automation projects and allocates a set of skill to an automated system that matches the allocated attributes. Based on the allocated functions, a system is suggested from the database minimising the difference between the suggested attribute and the automation system via a simple loss function giving a penalty for a missing attribute (calculated distance vector). However, the calculation method optimises a function highly penalising the lack of key parameters (PK = key parameter).

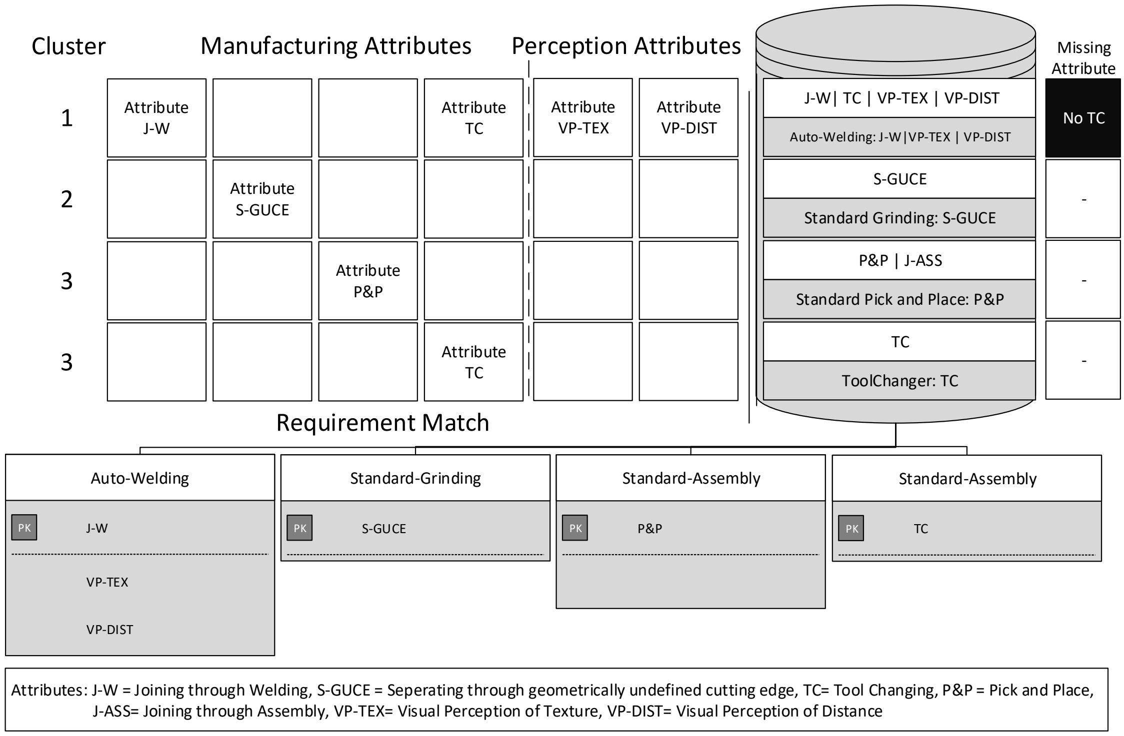


Figure 5-7: Functional Automation Component Mapping

Table 5-8 indicates that the clusters contain specific manufacturing attributes. Accessing the information, the user will now be able to select an automation system covering the required manufacturing sub-functions suggested based on the calculation of a loss function as previously described. The available manufacturing systems selection can be found on the right-hand side of the depicted table under ‘Application’.

In the toolbox (see section 5.3), the requirement engineering part has not been developed, since such a database does not currently exist. Instead, the user can select an application that is close to the represented process functions.

Table 5-8: Cluster Results as Process Functions - Welding Example.

Process Function	*Joining Through Welding*	*Cutting with geometrically undefined cutting edge*	*Pick and Place*	*Tool Changing and Setup*	*Assembly*	*Visual Perception Texture*	*Visual Perception Distance*	*App*
1	100%	0%	0%	25%	0%	100%	100%	Auto-Welding
2	0%	100%	0%	0%	0%	0%	0%	Standard Grinding
3	0%	0%	100%	0%	100%	0%	0%	Pick & Place
4	0%	0%	0%	75%	0%	0%	0%	Tool Change

Through the system design information pre-determined by the user, the automation system design uncertainty is significantly reduced. The users experience about the manufacturing process investigated has a measurable impact on the support framework. A lack of knowledge at the present step would lead to a misselection of a manufacturing process by the user. However, the thesis focuses on an early-stage decision-support for a business case evaluation. Therefore, the system design does not necessarily need to be fully determined. A functional representation of the task is assumed to be sufficient to continue the decision-making process. In section 5.2.2, the tool has transformed the manual task into a functional model. Section 5.2.3 will describe how a feasibility decision is made using expert knowledge for the individual process function.

5.2.3 Decision-Making for Automation Domain

The conceptual framework has divided the decision-making for the automation domain into three different parts. The parts represent the interconnectivity of the presented work with the requirement engineering (as previously pointed out), decision modelling, and the critical success factor assessment. From a practical perspective, the difference between the decision modelling and the critical success factors might not always be distinct. The decision factors and decision data influence the modelling of the decision process.

As previously described, the aim is to establish a feasibility model that builds upon the abstracted process functions. The literature review describes different methods for decision-making under uncertainty and in a risk context. Within the conceptual framework chapter, the use of a probabilistic model for the decision-making part of the framework is considered appropriate.

Currently, probability theory as the right instrument for risk assessment under uncertainty is subject to a controversial discussion. Besides critics about the effectiveness of probability theory itself, difficulties with the appliance of the theory have been reported. The difficulties are introducing additional methodological problems like the assessment of prior probabilities and the determination of factors used for the model [316].

Given a complete dataset, the calculation of numbers for analysis is not a major difficulty (use of historical data). For some applications, however, extracting strong statistical data in both, quality and quantity is not possible. Nonetheless, for statistical reasoning, the effect and frequency distribution of occurrences are generally obtained from a historical dataset [317]. In the conceptual framework, the scarcity of historical data was pointed out as a limitation in the decision environment. Consequently, a data-driven approach is not suitable for the risk assessment in this research, as a statistical model is constrained to an optimal approximation of the distributions based on the historical dataset. Weak statistical data will lead to a weak approximation of the problem [317]. Some experts, therefore, may argue against the application of probability theory with high uncertainty [318] and choose different approaches like fuzzy logic to create fuzzified and weighted expert decision factors.

A concern with the present methods is that a neglection of causal mechanisms in the dataset might lead to operational loss events [319]. As an alternative to statistical models, other considered models describe a causal relationship among factors (risk of operational losses approximation, see for example [320]). Among the linear and non-linear causal modelling techniques applied to date, Bayesian Belief Networks appear to be increasingly applied for knowledge-based probabilistic modelling [321].

The thesis adopts a Bayesian Belief Network for modelling expert knowledge. Despite external influences on the automation feasibility of a process, the investigation is limited to factors related to the manufacturing company. The starting point of a Bayesian Belief Network is i) a determination of critical success factors, and ii) a qualitative influence relationship using directional graphs.

A. Critical Success Factors

To obtain the critical success factors related to the manufacturing businesses, workshops with the industrial partners have been conducted. The aim of the workshops was to cover the factors for the implementation of intelligent automation using expert knowledge. After the factors have been identified, the respondents created a network using directional graphs to design the network among the critical success factors. The factors are connected using prior probability interviews based on the directed graph network. The interviews with the automation experts are one-to-one interviews to prevent misunderstandings. The following figure displays a graphical overview (see Figure 5-8). Due to data sensibility concerns of the manufacturing businesses, an exemplary network will be introduced influenced by the current automation literature to describe the framework modelling.

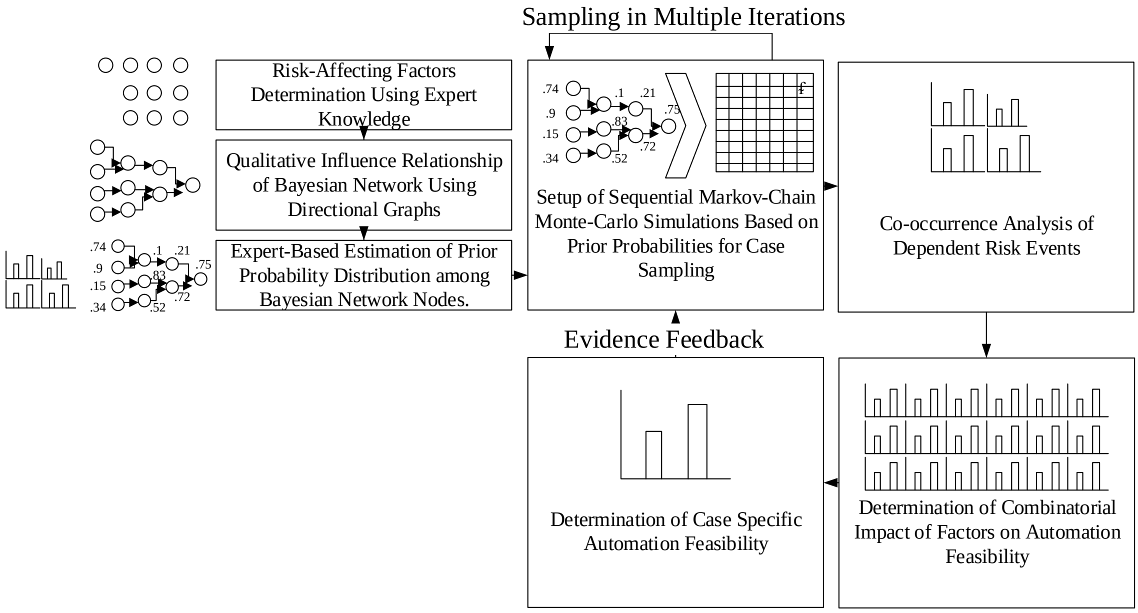


Figure 5-8: Bayesian Network with MCMC Sampling

The following section will present the data collection steps in more detail. Additionally, an artificial dataset will be introduced to explain the expert elicitation process. The underlying reason is the sensitivity of the expert data and a restriction to publish detailed business information. The result section will display real expert networks abstracted to a higher level. An artificial dataset is used to explain the dependency in more detail.

a. Critical Factors and Influence Relationship Using Directional Graphs

In the first step, an expert workshop was conducted, and the attendees were tasked to identify a list of critical success factors for the existing problem. In the artificial case (see

Figure 5-9), the problem is an evaluation of the technical complexity. Based on the identified factors, the respondents will have to create an influence diagram using directional graphs. From a methodological perspective, the investigator divided the experts into sub-groups. The groups were iteratively reunited enforcing a discussion on the experts to achieve a consolidation of the expert views based on different initial solutions (DELPHI-method). An exemplary influence diagram has been created based on the factors list on the right-hand side of Figure 5-9.

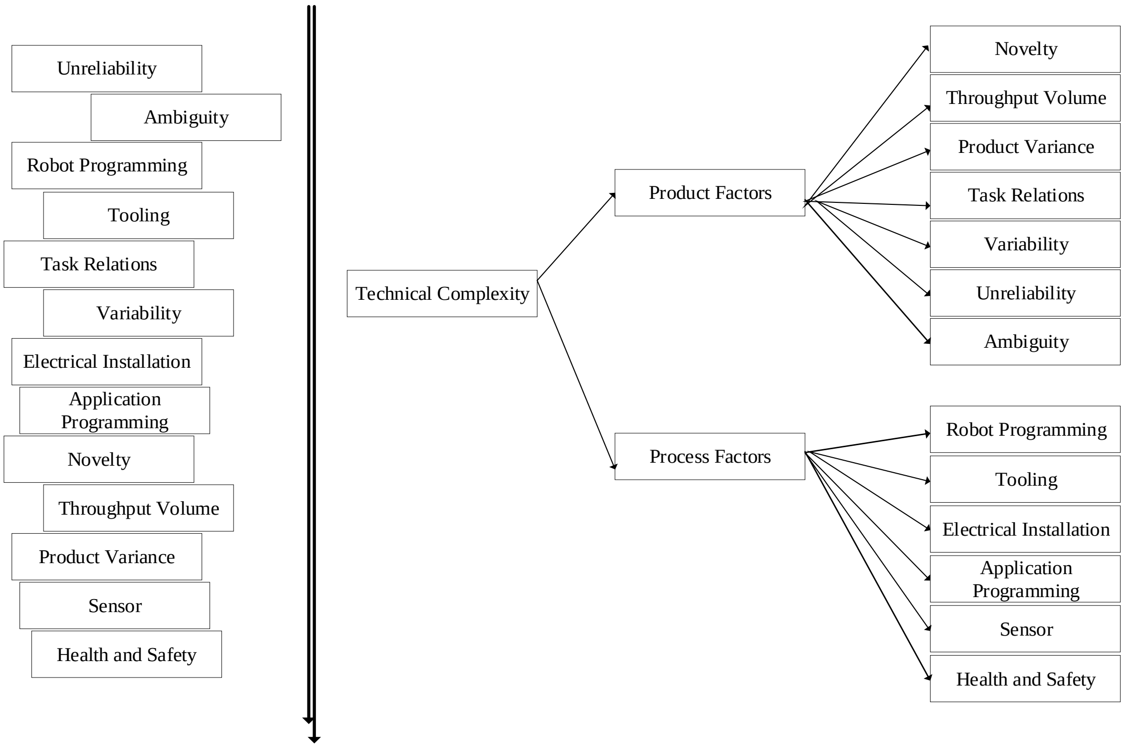


Figure 5-9: Factors List and Influence Diagram Using Directional Graphs – Literature Example.

b. *Expert-Based Estimation of Prior Probability Distribution among Bayesian Network Nodes*

After the directional graphs have been identified, one-to-one interviews with the experts were conducted numerically limited by the courtesy of the supporting companies. An expert interview lasted about 1 hour to establish the numeric relationships of the critical success factors. The access to expert pools releasing sensitive data about their automation process was restricted and must be considered a limitation of the presented thesis. Based on the expert interviews, prior probabilities were extracted. Figure 5-10 presents a comprehensive artificial dataset describing the product-driven complexity factors and the process-driven factors. Important factors from a process perspective were related to the different types of programming needed as well as to installations, tooling and sensors required. The inspiration was given by Groover [312].

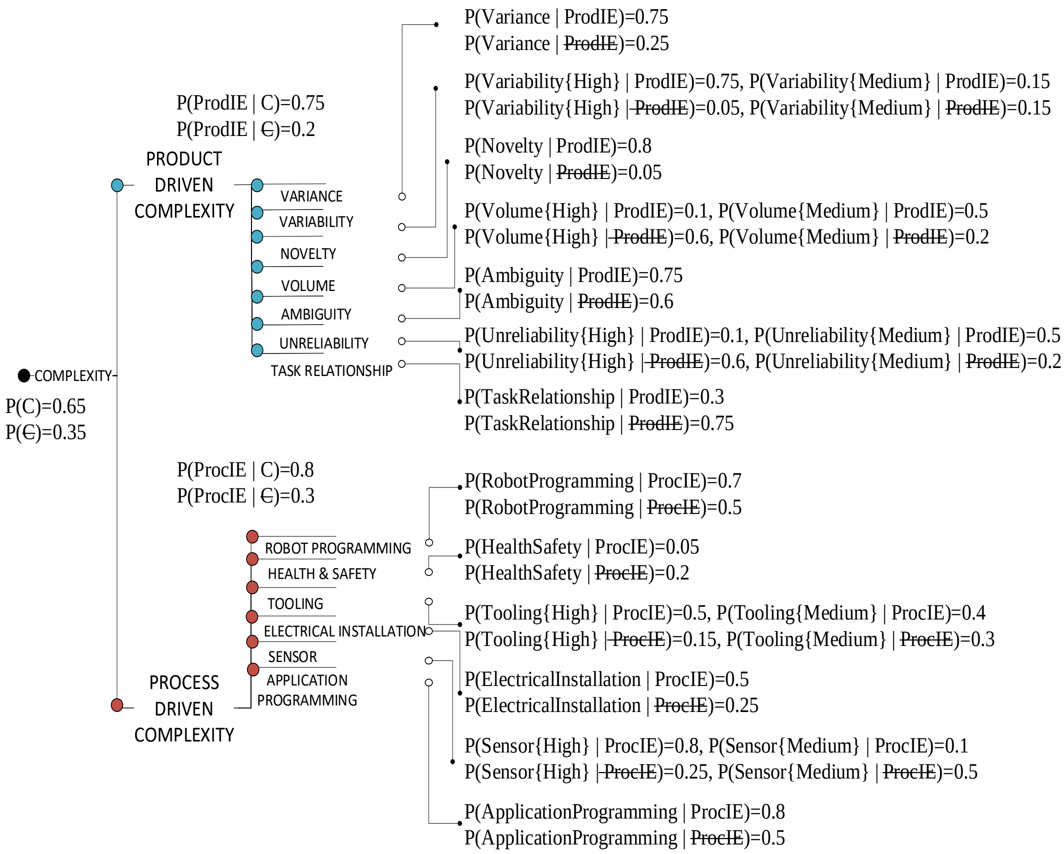


Figure 5-10: Example for Expert-Based Estimation Structure

Even though the numbers and factors may not be identical to the industrial results, a similar structure has been achieved. The information displayed indicates the effort required by the experts to create the actual database. On average, an individual expert interview lasted about an hour. Based on the prior probabilities, the individual impact of each factor on the success of automation can be obtained using the Bayesian Network rules.

B. Decision Modelling

Building upon the collected dataset, the decision-modelling can be approached. The first part of the following subsection introduces the basics of Bayesian Networks by an example of the artificial dataset.

a. The Theorem of Bayes and Bayesian Networks

Current approaches are mostly used for investment decision-making forcing the designers and planners to reduce uncertainty by assigning probabilistic values for future and present investment consumptions. The risk modelling emphasises on the impact of uncertainty on manufacturing planning decisions. A major source of uncertainty is driven by system design and cost projections and it was previously argued against the projection of costs at an early-stage (see chapter 5).

In the thesis experts' subjective probability distributions are evaluated for the influencing categories caused by the critical success factors. For the Bayesian Network, the following rules are applied: Given a finite set of random variables V (critical success factors), where each variable is described with a capital letter (e.g. X, Y, Z). Each state of the variable is described with a corresponding lowercase letter (e.g. x, y, z). All sets within a variable X are denoted as D_X with a probability distribution over the variable as Pr(X) and the corresponding probability of a state $x \in D_X$ as Pr(X=x) or Pr(x). A combination of multiple states for more than one critical success factor is called a scenario [322]. The basis of a Bayesian Network is the Theorem of Bayes.

Bayes Theorem

$$Pr(B|A) = \frac{Pr(A|B)\, Pr\,(B)}{Pr\,(A)} \qquad (9)$$

The starting probability is called P(A) and the posterior probability P(A|B) is the probability of A knowing the state of variable B. If A and B are independent, P(A)=P(A|B). The Bayes Theorem is the basis of a Bayesian Network. A Bayesian Network is a directed graph where the arrow A describes a probabilistic relation between the vertices and each vertex, $V \in V$ is the mathematical representation of a discrete variable. [322] The associated function of the vertexes $\theta_V \in V$: $DV \times D_{\Pi V} \rightarrow [0, 1]$ must fulfil the condition that for every possible combination of $\pi_v \in \Pi_V$ the following equation applies:

$$\sum_{d_v \in D_V} \theta_V\,(d_V, \pi_V) = 1\,. \qquad (10)$$

If there are two variables, A and B, which are sharing the probability distribution Pr(A,B). Pr(A) is calculated by taking the sum over the joint probability with all states of B.

$$\Pr(A) = \sum_{b_i \in D_B} \Pr(A, b_i). \tag{11}$$

To calculate and determine the representation of the joint probability distribution $\Pr(\Upsilon)$ within a Bayesian Network of discrete random variables Υ, the chain rule must be applied [322].

Chain Rule Theorem

$$Pr(\Upsilon) = \prod_{i=1}^{n} Pr(V_i, \Pi_{V_i}) . \tag{12}$$

Based on the chain rule, one can calculate the joint probability distribution for each *individual critical success factor*. The following example will be based on the factor 'Novelty' from the given dataset. The highlighted value in grey has been calculated as an example (see Table 5-9) from the values used in Figure 5-10.

$$\mathbf{Pr(Novelty, ProdIE, Complexity)} =$$
$$= \mathbf{Pr\,(Complexity)} * \mathbf{Pr(ProdIE|Complexity)} * \mathbf{Pr(Novelty|ProdIE)}$$

$$\Pr\,(\mathbf{Novelty, ProdIE, Complexity}) =$$

$$= 0.35*0.2*0.8 = 0.056$$

An iterative process of all combination leads to the creation of Table 5-9.

Table 5-9: Joint probability distribution – 'Novelty'-Example

P(Novelty, ProdIE, Complexity)				
ProdIE	Complexity	Novelty		
		Present	Absent	Marginals
High	Low	0.056	0.014	0.07
High	High	0.39	0.098	0.488
Low	Low	0.014	0.266	0.28
Low	High	0.008	0.154	0.163
Marginals		0.468	0.532	**1**

Based on the individual calculations, a table has been defined supporting the calculation of the *individual factorial* impact. To calculate the factorial impact, the following formula can be used:

Factorial Impact

$$Pr(A_x|C_y) = \frac{\sum_i^n \Pr(A_x, C_y, B_i)}{\sum_i^n \sum_j^m \Pr(A_j, C_y, B_i)} \tag{13}$$

In the exemplary case, the probability of a low complexity depending on present novelty according to the factorial impact formula would result in the following probability:

$P(\text{Complexity}_{\text{Low}} \mid \text{Novelty}_{\text{Present}}) = (0.056 + 0.014)/0.468 = 0.15$

The probability of low system complexity, given novelty is present, is determined as 15%. The following table related to the impact factor novelty would consequently look like the depicted table (see Table 5-10).

Table 5-10: Impact of Novelty on Complexity

P(Complexity|Novelty)		
Novelty	Complexity	
	Low	High
Present	0.15	0.85
Absent	0.526	0.474

Thus far, an explanation of how much the *individual critical success factors impact* the outcome was given by the mathematical procedure. The actual complexity of the problem, however, is the combinatorial calculation due to missing data. A combinatorial critical success factor impact cannot be easily obtained. The underlying reasons are related to missing dependency information:

- The individual probabilities cannot be used to obtain the combinatorial probability due to inter-factorial dependencies.
- If there are three different variables A, B, C and the sets of A and B are conditionally independent, given C, then for all $s_A \in D_A$, $s_B \in D_B$, and $s_C \in D_C$:
- *Conditional Independence*

$$Pr(s_A|s_B, s_C) = Pr\,(s_A|s_B). \quad (14)$$

It is impracticable, to ask the experts about factorial dependencies. In the given example 13 factors have been presented. Obtaining the interrelating dependencies would increase the number of questions by at least 156 additional questions assuming a variable can only take two different states.

Consequently, a decision was made to reduce the number of questions to the experts (Figure 5-10). The prior probabilities are sampled from the assumptions of underlying distributions, copula theory (highly affected by the correlation assumption), or the

Markov Chain Monte Carlo (MCMC) method. An artificial sampling algorithm is used to deduce the relationships between the factors based on artificial sampling.

b. *Sequential Markov Chain Monte Carlo for Risk Modelling*

According to the literature on risk modelling [3], random variables are typically approximated as multivariate distributions. The assumptions of specific underlying distributions, like bivariate normal, relies heavily on correlation. Despite multiple measurements of dependency, correlations are the preferred options to linearly relate variables [323]. However, in data science, a computed correlation among millions of variables may have no meaning or be related to confounding circumstances. The following example of a correlation between suicides by hanging, strangulation as well as suffocation and the US spending on science, space, and technology shows a 99% correlation (Figure 5-11). However, the research found that the common mystifying factor is inflation affecting both, electricity and education cost growth over time. The factor has a bigger impact on science than direct factors like costs of administration and government-funded student loans. At the same time, inflation affects private households and increases pressure on an individuum.

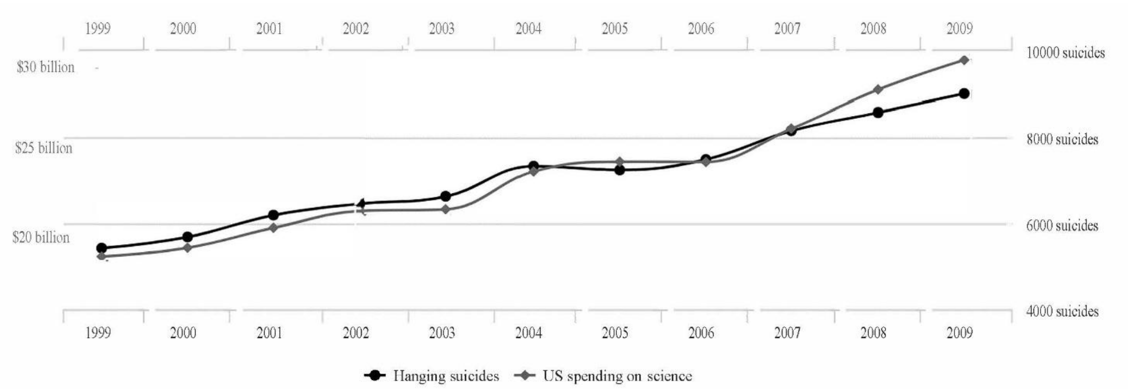


Figure 5-11: Example of a spurious correlation – US spending on science, space and technology with suicides by hanging, strangulation and suffocation.[5]

Such a methodological dependency on correlation has widely been blamed as contributing to a misinterpretation of risks (like the financial crisis in 2007/2008). A reliance on correlation to measure dependency between risks bears problems of extraordinary growth [323]. Using correlation or Gaussian copula theory to approximate

[5] See https://www.datasciencecentral.com/profiles/blogs/spurious-correlations-15-examples , last accessed on 10th of December 2018

dependencies between variables and risks neglect possibly existing tail dependencies and hidden dependencies. Smart argues that overrating correlation leads to an underestimation of risks mostly due to a neglect of joint extreme events (tail dependencies) [324]. Extreme events can cause a chain reaction with a possible extreme influence on other events. Consequently, the decision was against the use of theories that approximate results arising from the original distribution function. Specific events will be sequentially created via a sequential MCMC method.

In the decision theory, sequential MCMC methods are part of the Feynman-Kac particle models or also referred to as particle filter methods [325]. An example of a sequential Monte-Carlo method has been demonstrated within a BN-based costing simulation environment for construction cost estimations [206]. However, the specific application was facing complexities arising from a different stage of the decision-making process that required a sequential costing mechanism (strong, yet decreasing, cost-risk dependency over time in a construction scenario). To acknowledge tail effects, the aim is to connect the different events with prior distributions in a Markov-Chain simulating the individual distribution based on prior events. The foundation of a Monte-Carlo approach is the computation of a random occurrence of variables based on a weighted random sampling [326].

c. *Bayesian Network-Based Markov-Chain Monte-Carlo Method*

Monte Carlo methods for decision-making are not novel by any means. First applications were introduced by Hertz (1964) for financial risk assessment [327]. In the following application case, the experts connected the different decision factors in a BBN via posterior distributions. The initial dataset table shows, different factors carry different 'events', like task relationship (X = {goal := 0, sequential := 1}) or health and safety (Y = {fencing := 0, open :=1}). To mitigate the programming effort, every factorial outcome has been equipped with a specific value z that represents an event. Based on the artificial distribution of events, a sample of events is being created arising from the prior distribution set (Figure 5-12). The sample allows estimating the interdependencies and the impact of the decision variable set by co-occurrence analysis. The artificial sample is created via a sequential Monte Carlo approach simulating the value z based on the related parent value $z = \zeta\,(\Pr(A))$.

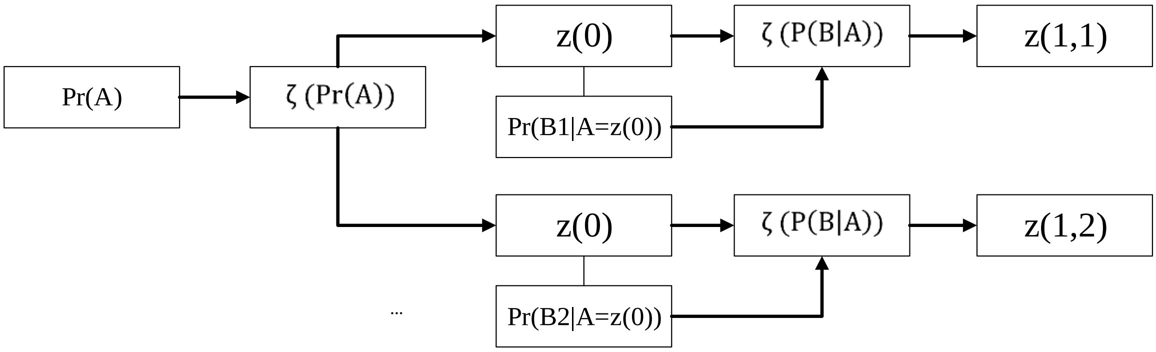


Figure 5-12: Conceptual Sequential Monte Carlo Method

The value z for every node is simulated using the consecutive Monte Carlo distribution ζ (P(B|A)) obtained from the related posterior distribution. In the specific case, a discrete multivariate distribution for the Monte Carlo simulation ζ (P(B|A)) of the value z related to the probability P(B) has been selected.

Value $z_{i,j}$ $$z_{ij} = \zeta(P(B_i|A_j)) \quad (15)$$

After each value has been sequentially simulated, the individual simulated cases x_i can be expressed in a matrix collecting the individual values $z_{i,j}$ for each of the simulated cases. The first element of the matrix has no prior distribution and, therefore, the value is created based on the simulation of P(A) only.

Case $C_{i,j,..,n}$ $$C_{ij} = \zeta(P(A) \quad ... \quad \zeta(P(B_i|A)) \quad ... \quad \zeta\left(P\left(C_j|B_i\right)\right) \quad \cdots \quad z_n \quad (16)$$

Case Matrix C_N $$C_{ij} = \begin{pmatrix} \zeta_0(P(A)) & \cdots & z_{0,n} \\ \vdots & \ddots & \vdots \\ \zeta_N(P(A)) & \cdots & z_{N,n} \end{pmatrix} \quad (17)$$

To obtain statistically solid results, the law of large numbers applies, which implies to increase the number of created samples as much as possible to obtain statistically reliable results (n → N). Over the frequency n of the specific cases, the estimated distribution $\hat{P}$ can be obtained. The distribution $\hat{P}$ presents the estimated probability for a combination of events based on the prior distribution by modelling expert probabilities.

$$\text{Estimated Distribution } \hat{P} \qquad \hat{P} = \frac{n(\zeta(P(A)|z_1, \dots, z_n)}{n(\zeta(P(A)|z_1, \dots, z_n) + n(\zeta(P(\bar{A})|z_1, \dots, z_n)} \tag{18}$$

Table 5-11 displays an example for the first 20 propagated cases produced by the MCMC method. For calculation reasons, the outcome has been produced in a specific way allocating a number to a state of the decision variable (High =2, Medium =1, Low=0; or High=1, Low=0,…). As can be obtained from Table 5-11, a high amount of artificial cases is created to be assessed. The indefinite amount of cases requires a mechanism to stop the simulation of the MCMC method as soon as the solution converges towards an acceptable solution.

Table 5-11: Case Matrix C(N) - Example.

Algorithmic logic for the Markov-Chain Monte-Carlo Method		*If P(A) then P(ProdIE)= 0.2;* Else P(ProdIE)= 0.75	*If P(ProdIE) then P(Novelty) = 0.8;* Else P(Novelty) = 0.05	*If P(ProdIE) then P(VolumeHi) = 0.1* Else P(VolumeHi) = 0.6,	*If P(ProdIE) then P(Variance)= 0.75;* Else P(Variance) = 0.25	*If P(ProdIE) then P(Relations)= 0.3;* Else P(Relations)= 0.75	*If P(ProdIE) then P(VariabilityHi)= 0.8;* Else P(VariabilityHi)= 0.05…	*If P(ProdIE) then P(UnreliableHi)= 0.1;* Else P(UnreliableHi)= 0.6,…	… …
Case	**Success**	ProdIE	Novelty	Throughput	Variance	Relationship	Variability	Unreliability	..
1	**0**	0	0	2	0	1	2	1	...
2	**1**	1	1	0	1	0	1	2	...
3	**0**	1	1	0	1	1	1	0	...
4	**0**	0	0	1	0	1	2	1	...
5	**0**	0	0	1	0	1	0	2	...
6	**1**	0	0	0	0	1	2	2	...
7	**0**	1	1	2	1	0	1	0	...
8	**0**	1	1	0	1	0	1	2	...
9	**1**	0	0	0	0	1	0	2	...
10	**0**	1	1	1	1	0	1	0	...
11	**0**	1	0	2	1	1	1	2	...
12	**0**	1	1	0	1	0	1	2	...
13	**0**	1	1	0	0	0	1	2	...
14	**0**	1	1	0	1	0	0	0	...
...	**0**	1	1	2	0	1	1	2	...

The standard deviation is selected as a requirement. The principal assumption is that the individual expert is not sure on a one-digit percent level (for example can defer between 5% or 8% percent on the question), but more likely on a two-digit percent level (can defer between 50% and 80 %) related to the one-on-one expert interview to assess the prior probabilities. Therefore, the introduced stopping criteria for the MCMC method is considered fulfilled when the standard deviation of the amount of created cases N does not exceed 10%.

Stopping Criteria N(s)

$$0 \xrightarrow{N} N_s = \begin{cases} if\ s = \sqrt[2]{\dfrac{\sum_{i=1}^{n}(\hat{x}_i - \overline{x})^2}{n-1}} < 0.1, N = N_s \\ else,\ \ N = N + + \end{cases} \qquad (19)$$

The realisation of the conceptual framework finally allows the development of a toolbox.

5.3 Toolbox

Thus far, the conceptual framework in Chapter 4 has introduced key components of the decision-support. Those key parts have been mathematically expressed in the previous section (Section 5.2). The following section explains, how the resulting mathematical model has been transformed into a toolbox, which allows the analysis of a real case scenario. The explanation of the toolbox will lead to the result section demonstrating the application of expert elicitation knowledge to real case scenarios.

5.3.1 Microsoft Excel

The toolbox has been created as a Microsoft Excel application. Since the industrial collaborators are not allowed to use unapproved software (like Java applications, or Python applications), the final decision was to create a Microsoft Excel application. An alternative was the development of an online tool. However, due to the complexity of an online application and difficulties to set up and maintain the application (databases, internet domain rights, connection to webmail services, data protection, and fees), a decision was taken against an online application and in favour of an Excel application. Microsoft Excel is a spreadsheet program encompassed in the Microsoft Office suite of tools. The presented spreadsheets display tables of values organised in rows and columns. The incorporated values can be deployed mathematically using arithmetic processes and functions. Establishing an environment for the realisation of the framework, the basic functions of Excel have been extended using the visual basic for applications (VBA) and the SimulAr Monte-Carlo simulation toolbox developed by Luciano Machain (2012)[6]. VBA is a programming language that enables the development of user-defined functions within the Excel environment. The SimulAr- extension will later enable to set up an MCMC method.

5.3.2 Toolbox

This sub-section introduces the decision support tool. The introduction of the tool is structured according to the chronological steps. The application starts with the user input of HTA data and classification before the clustering algorithm transforms the inputs into

[6] http://www.simularsoft.com.ar/

task functions. The individual function is then evaluated by a Bayesian Belief Network based on a determination of decision factors by the user.

A. HTA Analysis and Task Classification

The starting point of the decision support tool is presented in Figure 5-13. The column on the very left provides the opportunity to insert the hierarchical task structure (field 1). The head-row allows the user to select different manufacturing attributes applicable via a drop-down menu (field 2). The user is requested to attribute the manufacturing operations according to the hierarchy on the left-hand side. After the user has filled out the data sheet with the hierarchical task structure and gave attributes to the specific operations, the button ('intelligent automation') can be selected, which runs the clustering algorithm.

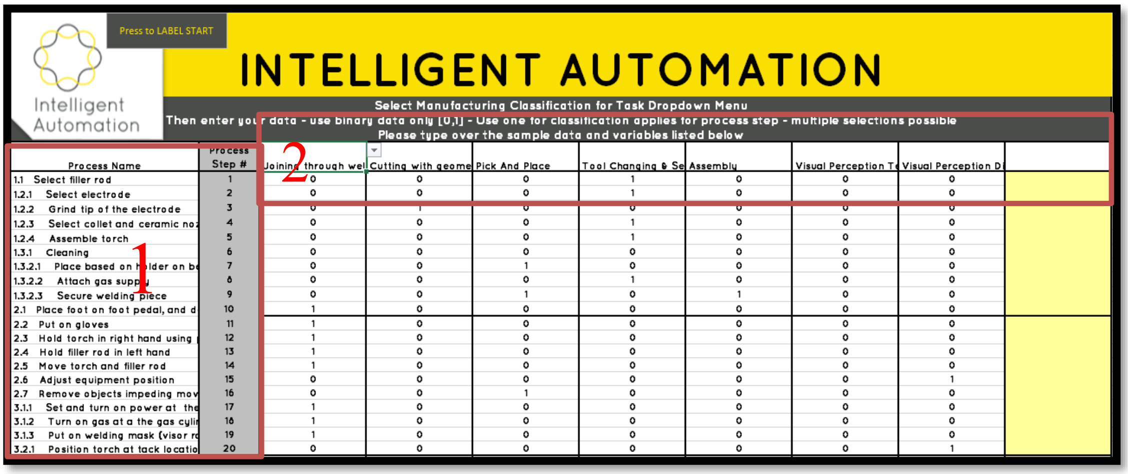
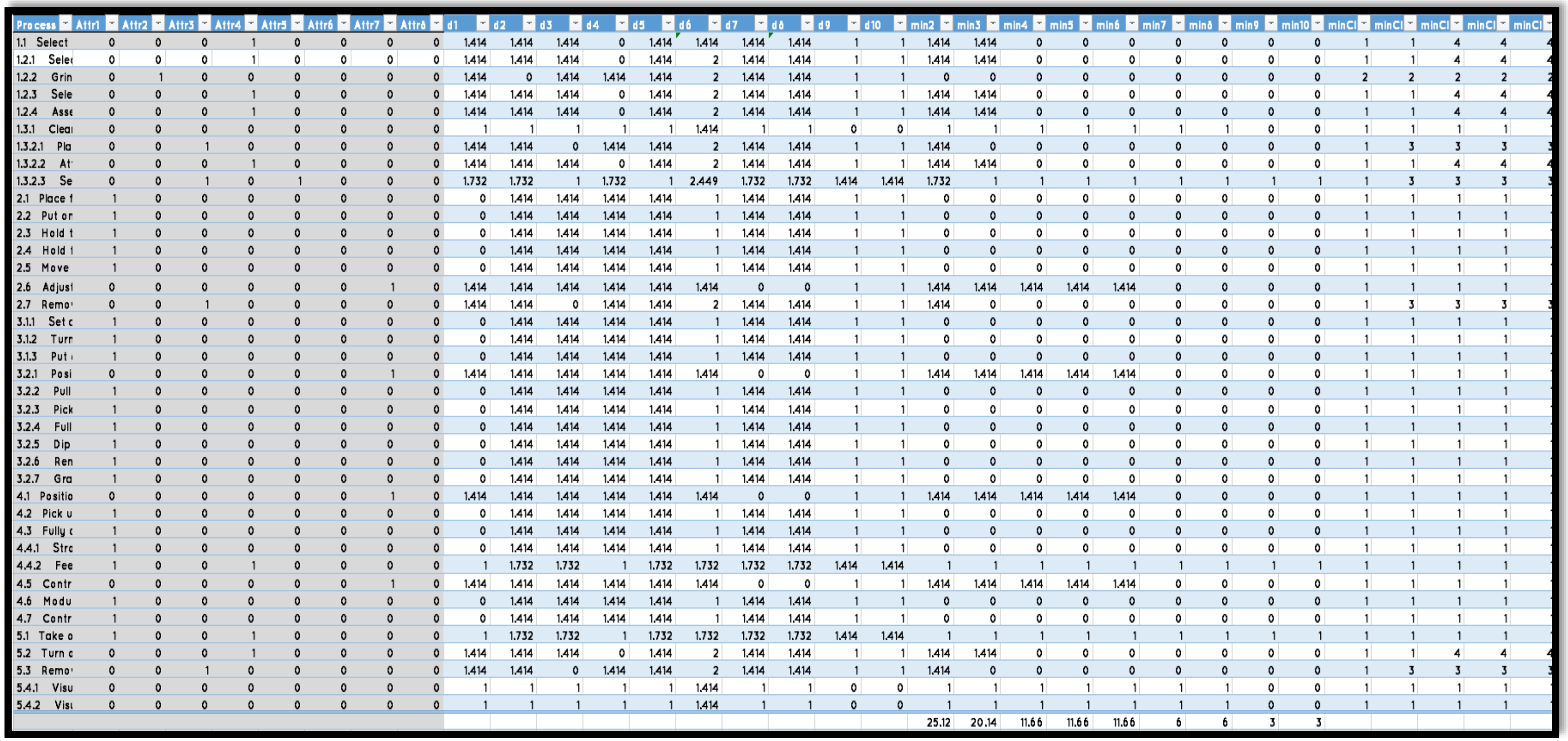


Figure 5-13: User Input Data

B. Clustering

The user input data are translated into a clustering table, as depicted in Figure 5-14. The clustering algorithm works based on the mathematic model described in section 5.2. However, within the tool, a maximum of 10 clusters is permitted. Reasons are the increased effort related to the creation and calculation of clusters. For the same reason, only 8 different manufacturing attributes are permitted for selection in the user input data sheet. If more attributes are required, dividing the hierarchical task into two separate tasks is suggested. The number of clusters and attributes was sufficient in processing the case study results (see Chapter 6).

The application of the clustering algorithm leads to a consecutive step, which requires user input. The user is automatically redirected to the consecutive sheet.



Process	Attr1	Attr2	Attr3	Attr4	Attr5	Attr6	Attr7	Attr8	d1	d2	d3	d4	d5	d6	d7	d8	d9	d10	min2	min3	min4	min5	min6	min7	min8	min9	min10	minCl	minCl	minCl	minCl	minCl
1.1 Select	0	0	0	1	0	0	0	0	1.414	1.414	1.414	0	1.414	1.414	1.414	1.414	1	1	1.414	1.414	0	0	0	0	0	0	0	1	1	4	4	4
1.2.1 Selec	0	0	0	1	0	0	0	0	1.414	1.414	1.414	0	1.414	2	1.414	1.414	1	1	1.414	1.414	0	0	0	0	0	0	0	1	1	4	4	4
1.2.2 Grin	0	1	0	0	0	0	0	0	1.414	0	1.414	1.414	1.414	2	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	2	2	2	2	2
1.2.3 Sele	0	0	0	1	0	0	0	0	1.414	1.414	1.414	0	1.414	2	1.414	1.414	1	1	1.414	1.414	0	0	0	0	0	0	0	1	1	4	4	4
1.2.4 Asse	0	0	0	1	0	0	0	0	1.414	1.414	1.414	0	1.414	2	1.414	1.414	1	1	1.414	1.414	0	0	0	0	0	0	0	1	1	4	4	4
1.3.1 Clea	0	0	0	0	0	0	0	0	1	1	1	1	1	1.414	1	1	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1
1.3.2.1 Pla	0	0	1	0	0	0	0	0	1.414	1.414	0	1.414	1.414	2	1.414	1.414	1	1	1.414	0	0	0	0	0	0	0	0	1	3	3	3	3
1.3.2.2 At	0	0	0	1	0	0	0	0	1.414	1.414	1.414	0	1.414	2	1.414	1.414	1	1	1.414	1.414	0	0	0	0	0	0	0	1	1	4	4	4
1.3.2.3 Se	0	0	1	0	1	0	0	0	1.732	1.732	1	1.732	1	2.449	1.732	1.732	1.414	1.414	1.732	1	1	1	1	1	1	1	1	1	3	3	3	3
2.1 Place f	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2.2 Put on	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2.3 Hold t	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2.4 Hold t	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2.5 Move	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
2.6 Adjust	0	0	0	0	0	0	1	0	1.414	1.414	1.414	1.414	1.414	1.414	0	0	1	1	1.414	1.414	1.414	1.414	1.414	0	0	0	0	1	1	1	1	1
2.7 Remo	0	0	1	0	0	0	0	0	1.414	1.414	0	1.414	1.414	2	1.414	1.414	1	1	1.414	0	0	0	0	0	0	0	0	1	3	3	3	3
3.1.1 Set c	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.1.2 Turn	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.1.3 Put	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.2.1 Posi	0	0	0	0	0	0	1	0	1.414	1.414	1.414	1.414	1.414	1.414	0	0	1	1	1.414	1.414	1.414	1.414	1.414	0	0	0	0	1	1	1	1	1
3.2.2 Pull	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.2.3 Pick	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.2.4 Full	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.2.5 Dip	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.2.6 Ren	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
3.2.7 Gra	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
4.1 Positio	0	0	0	0	0	0	1	0	1.414	1.414	1.414	1.414	1.414	1.414	0	0	1	1	1.414	1.414	1.414	1.414	1.414	0	0	0	0	1	1	1	1	1
4.2 Pick u	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
4.3 Fully c	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
4.4.1 Stra	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
4.4.2 Fee	1	0	0	1	0	0	0	0	1	1.732	1.732	1	1.732	1.732	1.732	1.732	1.414	1.414	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4.5 Contr	0	0	0	0	0	0	1	0	1.414	1.414	1.414	1.414	1.414	1.414	0	0	1	1	1.414	1.414	1.414	1.414	1.414	0	0	0	0	1	1	1	1	1
4.6 Modu	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
4.7 Contr	1	0	0	0	0	0	0	0	0	1.414	1.414	1.414	1.414	1	1.414	1.414	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1
5.1 Take o	1	0	0	1	0	0	0	0	1	1.732	1.732	1	1.732	1.732	1.732	1.732	1.414	1.414	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5.2 Turn c	0	0	0	1	0	0	0	0	1.414	1.414	1.414	0	1.414	2	1.414	1.414	1	1	1.414	1.414	0	0	0	0	0	0	0	1	1	4	4	4
5.3 Remo	0	0	1	0	0	0	0	0	1.414	1.414	0	1.414	1.414	2	1.414	1.414	1	1	1.414	0	0	0	0	0	0	0	0	1	3	3	3	3
5.4.1 Visu	0	0	0	0	0	0	0	0	1	1	1	1	1	1.414	1	1	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1
5.4.2 Visu	0	0	0	0	0	0	0	0	1	1	1	1	1	1.414	1	1	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1
																			25.12	20.14	11.66	11.66	11.66	6	6	3	3					

Figure 5-14: Clustering Algorithm Calculations

C. Sequential Process Identification

Row after row, the user can manipulate the 'Sequential Helper' displayed at the right-hand side of Figure 5-15. The sequential helper was a requirement of the conceptual framework to resolve problems with sequential dependencies. The method is applied using a message box asking the user for the specific input operation after operation. The two options are "Keep" or "Sequencing". The selection of "Sequencing" will allocate every following cluster with the same attribute in a new cluster. As an example, let us imagine a process allocated to cluster 4. However, due to the different scale of the manufacturing operation, the user believes that the process should be separated from the previous operations with the same manufacturing attributes (maybe the previous process was grinding but the following steps are related to polishing). Therefore, an indication should show that sequencing is required for a particular operation. Consequently, every following operation related to the same attributes will be allocated to a new cluster.

Processes	Class1	Clas:	Clas:	Class	Clas:	Class	Clas:	Class	Clust	elper
1.1 Select filler rod	0	0	0	1	0	0	0	0	4	Keep
1.2.1 Select electrode	0	0	0	1	0	0	0	0	4	Keep
1.2.2 Grind tip of the electrode	0	1	0	0	0	0	0	0	2	Keep
1.2.3 Select collet and ceramic nozzle	0	0	0	1	0	0	0	0	4	Keep
1.2.4 Assemble torch	0	0	0	1	0	0	0	0	4	Keep
1.3.1 Cleaning	0	0	0	0	0	0	0	0	1	Keep
1.3.2.1 Place based on holder on bench	0	0	1	0	0	0	0	0	3	Keep
1.3.2.2 Attach gas supply	0	0	0	1	0	0	0	0	4	Keep
1.3.2.3 Secure welding piece	0	0	1	0	1	0	0	0	3	Keep
2.1 Place foot on foot pedal, and depress	1	0	0	0	0	0	0	0	1	Keep
2.2 Put on gloves	1	0	0	0	0	0	0	0	1	Keep
2.3 Hold torch in right hand using pen grip	1	0	0	0	0	0	0	0	1	Keep
2.4 Hold filler rod in left hand	1	0	0	0	0	0	0	0	1	Keep
2.5 Move torch and filler rod	1	0	0	0	0	0	0	0	1	Keep
2.6 Adjust equipment position	0	0	0	0	0	0	1	0	1	Keep
2.7 Remove objects impeding movement	0	0	1	0	0	0	0	0	3	Keep
3.1.1 Set and turn on power at the welding set	1	0	0	0	0	0	0	0	1	Keep
3.1.2 Turn on gas at a the gas cylinder	1	0	0	0	0	0	0	0	1	Keep

Figure 5-15: Sequence Database

After the completion of sequential information for the functional task entity and dependency, a final presentation of the process functions can be presented.

D. Final Cluster Representation

The presentation of process functions contains the allocated attributes and the percentage of an allocated attribute. Based on the allocation of attributes, an application can be selected from a drop-down menu on the left-hand side. The drop-down menu is connected to a database containing already existing automation systems in the industry. However, the requirement engineering steps presented in the framing chapter have not yet been implemented. So far, this step of the tool relies on the user input. Future work is required to implement the requirement engineering step within the functionalities of the toolbox.

Reasons for not implementing the requirement engineering step is the lack of data and insufficient characterisation of automation systems in terms of their capabilities. Once specific systems have been defined in terms of their capabilities, the requirement engineering approach could be implemented.

Process Function	Joining through welding	Cutting with geometrically	Pick And Place	Tool Changing & Setup	Assembly	Visual Inspection	Visual Perception Distance		Application
1	100%	0%	0%	25%	0%	0%	100%	0%	WIG
2	0%	100%	0%	0%	0%	0%	0%	0%	Grinding
3	0%	0%	100%	0%	100%	0%	0%	0%	Assembly
4	0%	0%	0%	75%	0%	0%	0%	0%	Tool Changer

Figure 5-16: Final Clusters with Attribute Allocation[7]

E. User Input – Variable Determination

The specification of functions is followed by a determination of critical success factors. As presented in chapter 5, the experts have created a BBN with specific factors. The datasheet shown in Figure 5-17 requests the user input to specify the specific scenarios. The extracted critical success factors from the automation experts will later be represented in the depicted structure (see Figure 5-17). To rate the specific functions in terms of their suitability or automation feasibility, the user must select a value for the success factors.

[7] Writing in Figure modified for visibility reasons.

The factors used for the presentation of the tool are related to the artificial database. The results sheet will receive the individual results calculated from the Bayesian Network.

Product Factors								(Predicted) Process Factors					
Application	Uncontrolle d Variablity	Volume	Product Variance	Relationship between	Variablity	Ambiguity	Unreliability	Robot Programmin	Tooling	Electrical Installation	Application Programmin	Sensor	Health and Safety
WIG	Present	Medium	Present	Goal	Medium	Absent	High	Complex	Moderate	Complex	Complex	Hard	Fencing
Grinding	Absent	Medium	Absent	Goal	Medium	Absent	Low	Moderate	Intuitive	Moderate	Moderate	Moderate	Open
Pick and Place	Absent	Medium	Present	Goal	Low	Absent	Low	Moderate	Intuitive	Moderate	Moderate	Intuitive	Fencing
Tool Changer	Absent	Medium	Present	Goal	Low	Absent	Low	Moderate	Intuitive	Moderate	Moderate	Intuitive	Fencing

Figure 5-17: Factorial User Input Sheet

Based on the user input, the results can be obtained from the various calculation databases and structurally presented. The individual factorial input is calculated and can be extracted first. The direct influences of individual decision factors are obtained from the Bayesian chain rule described in section 6.1.3.B. Figure 5-18 displays only one branch of the Bayesian network calculations using the chain rule theorem. For the calculation of the combinatorial influence of each factor, the described sequential MCMC method was applied to the underlying expert knowledge. The principle behind the method is a sequential application of a Monte-Carlo simulation linking prior probabilities.

F. Markov-Chain Monte-Carlo Sampling

Figure 5-19 displays an example of the computed sampling values based on the artificial database. For the application of the MCMC sampling, a conditional algorithm was designed, which uses the Monte-Carlo distributions of the SimulAR toolbox. The VBA code can be found in Appendix D. The underlying assumption is a multivariate discrete distribution linked to the conditional expert input, which was obtained via expert elicitation. With the exception of the first row of the figure, the data input of each variable is connected to the previous variable value. Based on the chain-like connection, an artificial sample to extract a close-to-reality approximation of the combined factorial influences can be established. Iteratively, an artificial sample is created based on prior probabilities. This means that the following value within the database is conditionally connected via MCMC to the previous value. Because of different categorical inputs for the variables, every categorical value was translated into a numerical value (e.g. high = 2, medium = 1, 0 = low). In this way, the computer-generated database represents a sample of the BBN-tree-structure and enables frequency considerations in the following step. It should be noted that due to the number of possible combinations even in small BN-trees, a large amount of computing has to be performed to decrease the standard deviation of the computer-generated database.

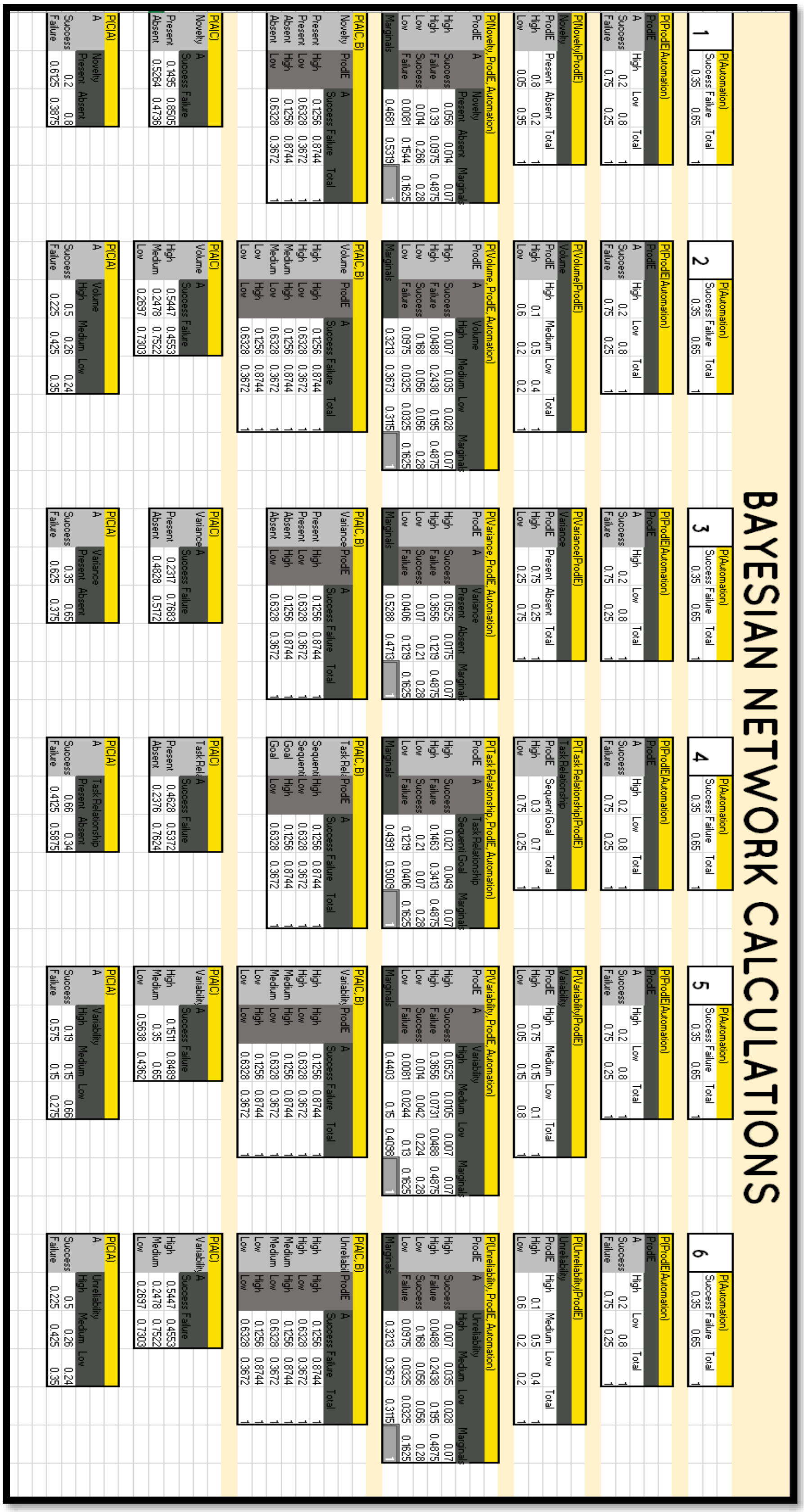


Figure 5-18: Bayesian Network Calculation Using Chain Rule Theorem.

	P(A)= 0.35	If P(A) then P(ProdIE)= 0.2; Else P(ProdIE)= 0.75	If P(ProdIE) then P(Novelty)= 0.8; Else P(Novelty)= 0.05	If P(ProdIE) then P(VolumeHi) = 0.1 Else P(VolumeHi) = 0.6,…	If P(ProdIE) then P(Variance)= 0.75; Else P(Variance)= 0.25	If P(ProdIE) then P(Relations)= 0.3; Else P(Relations)= 0.75	If P(ProdIE) then P(Variability Hi)= 0.8; Else P(Variability Hi)= 0.05…	If P(ProdIE) then P(UnreliableHi)= 0.1; Else P(UnreliableHi)= 0.6,…	…
Case	Succes	ProdI	Novel	Throu	Varial	Relati	Varial	Unrel	Ambig
10	0	1	1	1	1	0	1	0	1
11	0	1	0	2	1	1	1	2	1
12	0	1	1	0	1	0	1	2	1
14	0	1	1	0	1	0	0	0	1
20	1	1	1	0	1	0	1	2	1
27	0	1	0	2	1	1	1	0	1
28	0	0	0	1	0	1	0	1	0
31	0	0	0	2	1	1	2	1	0
38	1	0	0	1	0	1	2	2	0
39	1	0	0	2	0	1	2	1	1
41	0	1	1	0	0	0	1	0	1
42	0	0	0	1	0	0	2	1	0
45	0	1	1	2	0	0	1	2	1
56	0	1	1	0	1	0	0	2	0
59	0	0	0	2	0	1	2	1	0
78	0	0	0	0	1	0	2	1	0
105	0	1	1	2	1	0	1	0	0
106	1	0	0	2	0	0	2	1	1
107	0	1	1	0	0	0	1	2	0
132	0	1	1	2	1	0	1	0	0
136	0	1	1	1	0	0	1	0	1
137	0	1	1	2	1	0	0	2	1
142	0	1	1	1	1	1	1	0	1
152	1	0	0	1	0	1	0	0	1
160	0	1	0	0	1	1	1	0	1
161	0	1	1	2	1	0	2	2	1
163	0	1	1	0	1	0	1	0	1
165	0	1	1	1	0	0	1	1	0
168	0	0	0	1	0	1	0	2	1

…

Figure 5-19: Markov-Chain Monte-Carlo Sampling Database.

After the setup of the MCMC method, a database was calculated by counting the frequencies of the computer-generated cases. Based on the artificial sampling in combination with the frequency count of the cases, the combinatorial results for the given variables as depicted in Figure 5-20 have been extracted. In the figure, only one branch of the calculation was displayed again for reasons of clarity and comprehensibility.

Robot Programming	Tooling	Electrical Installation	Application Programming	Sensor	Health and Safety	Case Frequency	Success Case Frequency	ProcIE Cases	ProdIE High	Case Success
Complex	Hard	Complex	Complex	Hard	Fencing	25	6	19	0.76	0.24
Moderate	Hard	Complex	Complex	Hard	Fencing	18	7	6	0.333	0.38889
Complex	Moderat	Complex	Complex	Hard	Fencing	18	4	15	0.833	0.22222
Moderate	Moderat	Complex	Complex	Hard	Fencing	8	3	6	0.75	0.375
Complex	Intuitive	Complex	Complex	Hard	Fencing	10	4	9	0.9	0.4
Moderate	Intuitive	Complex	Complex	Hard	Fencing	7	3	3	0.429	0.42857
Complex	Hard	Moderate	Complex	Hard	Fencing	24	8	15	0.625	0.33333
Moderate	Hard	Moderate	Complex	Hard	Fencing	13	6	5	0.385	0.46154
Complex	Moderat	Moderate	Complex	Hard	Fencing	23	8	11	0.478	0.34783
Moderate	Moderat	Moderate	Complex	Hard	Fencing	10	4	4	0.4	0.4
Complex	Intuitive	Moderate	Complex	Hard	Fencing	22	9	16	0.727	0.40909
Moderate	Intuitive	Moderate	Complex	Hard	Fencing	14	5	6	0.429	0.35714

Figure 5-20: Frequency-based Calculation of Combinatorial Results.

The step was iteratively repeated and investigated. As stated within the framing chapter, with the applied method the probabilities converge after a large number of samples. A large number of samples was created, and the samples were evaluated statistically calculating the average of the sample cases, the standard deviation and the confidence (t)-interval with a significance value of 0.99 %. Some initial results are shown in Figure 5-21. The results have been extracted from an interrupted simulation to demonstrate how the stopping criteria work. The figure, however, only displays one branch of the BBN.

In this case, the highest standard deviation is reported as 0.2513 with a confidence interval of 0.08 (reddest marked field). The linked branch factors were identified as (Robot Programming = Moderate, Tooling = Intuitive, Electrical Installation = Complex, Application Programming = Complex, Sensorics = Moderate, Health and Safety = Fencing). The results suggest that given artificial prior probabilities, the specific case presented the largest discrepancy of the related automation feasibility output based on the standard deviation.

The stopping criteria, however, requires every standard deviation to be smaller than 10% as according to the stopping criteria presented in section 5.2.3.B. Therefore, the sheet suggests a continuation of the simulation. The calculation is done iteratively (in batches as a full calculation of all the numbers is required for one whole network) in Excel until the stopping criteria have finally been reached. The highest standard deviation at the displayed point in time is 25% and, consequently does not fulfil the conditions of the stopping criteria (10%).

The simulation will continue until the simulation produces results that satisfy the criteria. To achieve the stopping criteria, about 10 Million individual cases have been created on average for the different decision trees, which took around 140-150h per network using Excel VBA. However, the calculation of the results in the future may be better simulated using programming languages like C++ which would reduce the simulation time to around 10-20h.

AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK
																				Average	Standard Distribution	Confidence Interval
0.25	0.192	0.115	0.1	0.19	0.333	0.227	0.267	0.188	0.25	0.156	0.074	0.35	0.1	0.233	0.292	0.278	0.231	0.154	0.235	0.208268941	0.085651288	0.026369504
0.286	0.083	0.167	0.053	0.462	0.357	0.273	0.353	0.364	0.333	0.143	0.2	0.308	0.222	0.25	0.083	0.333	0.05	0.214	0.071	0.229437419	0.110422009	0.033995678
0.13	0.238	0.333	0.333	0.167	0.16	0.185	0.25	0.095	0.292	0.188	0.211	0.077	0.222	0.05	0.136	0.211	0.154	0.375	0.278	0.212903121	0.090132753	0.027749214
0.091	0.133	0.222	0.444	0.222	0.25	0.231	0.167	0.059	0.05	0.125	0.545	0.333	0.222	0.188	0.714	0.111	0.333	0.214	0.333	0.265744956	0.140803411	0.043349215
0.556	0.5	0.467	0.5	0.5	0.143	0.375	0.455	0.714	0.4	0.375	0.125	0.5	0.4	0.308	0.333	0.5	0.7	0.333	0.25	0.415909068	0.16742967	0.051546654
0.6	0.4	0.75	0.667	0.667	0.333	0.5	0.333	0.5	0.5	0.5	0.667	0.667	0.385	0.25	0.571	0.167	0.667	0.75	0.6	0.500594036	0.176973382	0.054484881
0.05	0.037	0.148	0.056	0.188	0.273	0.229	0.185	0.118	0.242	0.3	0.103	0.2	0.208	0.069	0.143	0.143	0.125	0.258	0.207	0.202026683	0.09227025	0.028407287
0.19	0.273	0.294	0.158	0.385	0.5	0.25	0.125	0.222	0.294	0.125	0.357	0.462	0.333	0.333	0.111	0.267	0.308	0.286	0.182	0.259141433	0.116514254	0.0358713
0.167	0.3	0.303	0.5	0.37	0.267	0.182	0.286	0.375	0.143	0.333	0.325	0.321	0.281	0.184	0.194	0.355	0.45	0.28	0.435	0.296250356	0.086113367	0.026511764
0.385	0.25	0.4	0.333	0.182	0.438	0.133	0.5	0.3	0.533	0.533	0.429	0.294	0.313	0.278	0.421	0.667	0.571	0.583	0.176	0.40140393	0.132969674	0.040937438
0.556	0.538	0.353	0.538	0.5	0.519	0.481	0.571	0.308	0.467	0.313	0.412	0.381	0.708	0.5	0.353	0.25	0.458	0.556	0.542	0.496545738	0.128451988	0.039546576
0.684	0.667	0.5	0.583	0.579	0.333	0.476	0.471	0.778	0.667	0.231	0.8	0.875	0.769	0.619	0.5	0.615	0.615	0.6	0.867	0.601219433	0.12172249	0.037474762
0.667	0.333	0.5	0.05	0.667	0.222	0.3	0.286	0.125	0.25	0.167	0.125	0.286	0.05	0.2	0.05	0.111	0.333	0.2	0.167	0.25585077	0.160231493	0.049330548
0.05	0.05	0.25	0.75	0.5	0.05	0.05	0.6	0.05	0.111	0.333	0.286	0.6	0.05	0.667	0.5	0.375	0.2	0.2	0.05	0.250681217	0.189337024	0.058291282
0.429	0.05	0.286	0.333	0.4	0.05	0.3	0.455	0.556	0.5	0.667	0.4	0.2	0.357	0.8	0.5	0.25	0.25	0.222	0.5	0.299229197	0.176174466	0.054238919
0.05	0.375	0.5	0.2	0.5	0.2	0.25	0.6	0.5	0.143	0.4	0.333	0.5	0.05	0.05	0.333	0.5	0.25	0.5	0.5	0.364371693	0.192764924	0.059346631
0.05	0.222	0.5	0.571	0.05	0.4	0.2	0.667	0.667	0.4	0.429	0.05	0.6	0.4	0.6	0.25	0.429	0.333	0.75	0.273	0.464816295	0.214676086	0.066092431
0.8	0.05	0.125	0.1	0.333	0.1	0.6	0.692	0.05	0.75	0.75	0.6	0.6	0.1	0.25	0.1	0.375	0.75	0.333	0.667	0.461492165	0.251532468	0.077439424
0.429	0.571	0.273	0.231	0.625	0.571	0.333	0.286	0.333	0.455	0.333	0.167	0.3	0.05	0.091	0.231	0.444	0.75	0.3	0.2	0.319072336	0.174370203	0.05368344
0.167	0.2	0.889	0.333	0.4	0.333	0.25	0.8	0.25	0.25	0.667	0.5	0.6	0.4	0.286	0.2	0.636	0.667	0.1	0.5	0.417993627	0.20338206	0.062615334
0.462	0.357	0.111	0.231	0.05	0.462	0.533	0.5	0.308	0.6	0.231	0.235	0.75	0.5	0.125	0.462	0.462	0.25	0.235	0.667	0.447773716	0.155610336	0.04790783
0.667	0.545	0.5	0.533	0.571	0.5	0.733	0.167	0.455	0.444	0.667	0.6	0.6	0.636	0.385	0.25	0.556	0.6	0.273	0.6	0.585496648	0.143962129	0.044321691
0.474	0.429	0.636	0.611	0.667	0.667	0.818	0.692	0.533	0.529	0.917	0.643	0.571	0.5	0.769	0.412	0.75	0.538	0.583	0.769	0.607517947	0.150047488	0.046195193
0.643	0.647	0.1	0.75	0.611	0.583	0.842	0.5	0.875	0.5	0.9	0.857	0.385	0.455	0.533	0.6	0.692	0.714	0.385	0.8	0.635815286	0.156454751	0.048167801
0.167	0.667	0.625	0.4	0.5	0.1	0.25	0.75	0.6	0.5	0.25	0.333	0.05	0.2	0.333	0.2	0.05	0.5	0.286	0.1	0.290436508	0.189766407	0.058423476
0.25	0.05	0.5	0.333	0.667	0.667	0.25	0.667	0.2	0.5	0.05	0.05	0.05	0.05	0.333	0.5	0.05	0.5	0.05	0.167	0.280833333	0.229589509	0.070683834

Figure 5-21: Example of Iterative Statistical Analysis as Stop-Clustering Condition

The results of the statistical analysis are fed back to the results sheet depicted in Figure 5-22. Multiple different values are presented in the result table. Firstly, the different established task functions are represented in the results sheet. The advantage of the presentation is the individual feasibility evaluation of each process function. The current presentation enables the user to identify solutions, where partial automation is more applicable. Every process function is evaluated individually by calculating the individual factor impact numbers. The individual factors are then combined to calculate the parent node (in the case "product-driven effort" and "process-driven effort)). For the calculation of the individual factorial impact, the results from the Bayesian Network Chain Theorem have been used. The combinatorial impact is related to the MCMC method. The individual calculation of the process- and product-driven effort results in the calculation of the overall score. This way, the individual "overall score" is obtained for every individual task function.

Function	Product Factors Impact	Impact Automation	Product Driven Effort	Automation Success	Process Factor Impact	Factorial Impact Automation	Process Driven Effort	Automation Success	OVERALL SCORE
WIG	Novelty	15	99	8	Robot Programming	31	83	22	
	Volume	25			Tooling	32			
	Variance	23			Electrical Installation	28			
	Task Relationship	24			Application Programmi	46			
	Variability	35			Sensor	24			
	Unreliability	27			Health and Safety	51			
	Ambiguity	41							15
Grinding	Novelty	53	50	50	Robot Programming	41	39	37	
	Volume	25			Tooling	54			
	Variance	48			Electrical Installation	40			
	Task Relationship	24			Application Programmi	74			
	Variability	35			Sensor	53			
	Unreliability	27			Health and Safety	33			
	Ambiguity	41							43
Pick and Place	Novelty	53	33	99	Robot Programming	41	57	43	
	Volume	25			Tooling	54			
	Variance	23			Electrical Installation	40			
	Task Relationship	24			Application Programmi	0			
	Variability	56			Sensor	46			
	Unreliability	27			Health and Safety	51			
	Ambiguity	41							71
Tool Changer	Novelty	0	33	99	Robot Programming	41	57	43	
	Volume	0			Tooling	54			
	Variance	0			Electrical Installation	40			
	Task Relationship	0			Application Programmi	0			
	Variability	0			Sensor	46			
	Unreliability	0			Health and Safety	51			
	Ambiguity	0							71

Figure 5-22: Factorial and Combinatorial Input and Calculation Results- Artificial Data.[8]

A detailed description of the applied algorithms can be found in Appendix D (in VBA code). Every individual datasheet that can be seen by the user of the toolbox as well as provided the detailed algorithms developed as part of the toolbox have been included (see Appendix D).

Based on the description of the toolbox, the results obtained through the application of the toolbox shall be presented using the collected case studies. The toolbox applied to the

[8] Figure modified for visibility reasons

presented case studies is, therefore, used as a functionality validation. The results of the clustering algorithms are compared to the IDEF0 results of automation experts. The quantitatively extracted automation decision factors will be used to assess the expert knowledge provided by the Manufacturing Technology Centre (MTC). Due to previous experiences, an expectation is that the insititution will present a technology-specific view on the automation problem. Therefore, the partner (MTC) has been influenced not to take a business, but a technical perspective on the intelligent automation problem. The results will justify the perspective later (see Chapter 7). As a consequence, the focus of the network will be on the technical aspects of the early-stage decision-making for intelligent automation.

6 Framework Validation

“The logic of validation allows us to move between the two limits of dogmatism and scepticism.” – Paul Ricoeur

Chapter 5 and 6 have introduced the concept and realisation of the framework for implementing intelligent automation in manufacturing businesses. These have fulfilled the framework requirements. The framework started from the task analysis and human factor domain and later demonstrated how the clustering algorithm extracted functions based on a classification scheme. The extracted process functions led to task component mapping supported via a requirement engineering approach. This step has not been implemented in the developed toolbox due to a lack of automation hardware data. The automation success rate for the individual process function has been estimated using the Bayesian Belief Network, where the combinatorial factors were obtained with the use of a Markov Chain Monte Carlo Method. The following sections demonstrate the main results throughout the collected case studies. For the framework validation, the establishment of the appropriate detail for human task attribution, the transition of the manual process into process modelling and representation, as well as decision-making for intelligent automation have been presented. First, section 7.1 will present the results related to the conceptual framework dealing with the task analysis and human factor domain, section 7.2 with the process representation and modelling domain, as well as section 7.3 with the decision-making for automation domain. The results are summarised in section 7.4.

6.1 Task Analysis and Human Factor Domain

As pointed out in the previous chapter, as part of the task analysis and human factor domain, the collected case studies were described using a specific sub-goal template (SGT) structure. The created database structure was presented in Figure 5-4. The use of the structure initially allowed the description of every operation on an action level. The specific template chosen for the investigation can be seen in the following Table 6-1. The structure describes actions for both, physical and cognitive tasks. The user is limited to a specific range of actions, which can be selected.

Table 6-1: Sub-Goal Template Structure developed based on [42]**.**

Physical action (P)	*Abbrev.*	*Body part*	*Movement*	*Cognitive action (C)*	*Abbrev.*	*Perception via*
Balancing	B1	Foot	Straight	Activate	A1	Nose
Bending	B2	Leg	Curve	Adjust	A2	Eyes
Climbing (step stool)	C1	Knee	Edge	De-activate	A3	Feeling/Touching
Crawling	C2	Finger		Read	C1	Hearing
Crouching	C3	Hand		Record	C2	Taste
Driving	D1	Wrist		Wait for Information	C3	
Grasp	G1	Arm		Receive information	C4	
Hearing	H1	Elbow		Give information	C5	
Jogging	J1	Shoulder		Remember	C6	
Kneeling	K1	Head		Retrieve	C7	
Ladders (ascend/ descend)	L1	Torso		Monitoring	M1	
Lifting	L2	Head		Monitor rate of change	M2	
Moving (translational)	M1			Inspect equipment/part	M3	
Moving (rotational)	M2			Diagnose process problems	D1	
Pressing	P1			Adjust plan/process	D2	
Pulling	P2			Locate contaminant factor	D3	
Pushing	P3			Judge adjustment	D4	
Reaching	R1					
Reaching above shoulder	R2					
Reaching below shoulder	R3					
Rotating Object	R4					
Seeing	S1					
Sitting	S2					
Spread	S3					
Stairs (ascend/ descend)	S4					
Standing	S5					
Stooping	S5					
Twisting	T1					
Walking	W1					

The application of the template in combination with the predetermined structure of the database has led to a complicated structure of actions, partially performed by the operator at the same time. The following Table 6-2 displays an example of the executed task analysis on an action level based on threaded fastener assembly. The case study was selected due to a lack of sensitive information a threaded fastener assembly process contains.

Table 6-2: Structure of Process Analysis on Action Level – Threaded Fastener Assembly.

HTA-Level	*Inter. Mov.*	*Ph. Act. Left*	*Part*	*Ph. Act Rig.*	*Part*	*Cog. Act. Tool*	*Percept. Sense*	*Cognitive Parameter*	*Cog. Act. Obj.*	*Percept. Sense*	*Cognitive Parameter*
1.1 Select socket head screw type	static	0	0	0	0	0	0	0	M3, M3	Eyes, Eyes	Size, Position
1.2 Set up fastening tool	trans										
1.2.1 Select fastening bit	trans	0	0	0	0	M3, M3	Eyes, Eyes	Size, Position	0	0	0
1.2.2 Assembly fastener and bit	trans/ rot	R3, G1, M1/ M2, R3	Arm, Hand	R3, G1, M1/ M2, P1	Arm, Hand	M1, A1, A2, A1, A2, A3	Eyes, Feeling, Eyes, Feeling, Eyes, Feeling	Position, Pressure, Position, Pressure, Position, Pressure	M1, A1, A2, A1,	Eyes, Feeling, Eyes, Feeling	Position, Pressure, Position, Pressure
1.3 Prepare parts for assembly	trans/ rot	0	0	R3, G1, M1/ M2	Arm, Hand	0	0	0	M1, A1, A2, A1	Eyes, Feeling, Eyes, Feeling	Position, Pressure, Position, Pressure
2 Align screw with threaded hole											
2.1 Pick-up screw	trans/ rot	0	0	R3, G1, M1/ M2	Arm, Hand	0	0	0	M1, A1, A2, A1	Eyes, Feeling, Eyes, Feeling	Position, Pressure, Position, Pressure
2.2 Align screw with threaded hole											
2.2.1 Gently slide screw along surface to find hole	trans			M1	Arm, Hand	0	0	0	A1, M2	Feeling, Feeling	Force, Pressure
2.2.2 Gently apply pressure to adjust ankle of screw in hole	trans/ rot	M1, R4			Arm, Hand	0	0	0	A1, M2, A1	Feeling, Feeling, Feeling	Pressure, Pressure, Momentum
3 Position fastener on screw head											
3.1 Pick-up screw driver	trans/ rot	R3, G1, M1/ M2	Arm, Hand	0	0	M1, A1, A1/ A2	Eyes, Feeling, Feeling/ Eyes	Position, Pressure, Position/Force	0	0	0
3.2 Position fastener on screw head	trans/ rot	M1, R4	Arm, Hand	0	0	M1, A1/ A2	Eyes, Feeling/ Eyes	Position, Position/Force	0	0	0
3.3 Stabilise screw with other hand	static	0	0	P1	Arm, Hand	0	0	0	A2, A2	Feeling, Feeling	Pressure, Position
4 Activate screwdriver tool											
4.1 Gently press trigger to activate screwdriver tool until it grips	trans	P1	Finger	B1	Arm, Hand	A2, A1	Feeling, Feeling	Pressure, Pressure	A2	Feeling	Position
4.2 Press trigger to fully activate screwdriver	trans	P1	Finger	B1	Arm, Hand	A2, A1, M2	Feeling, Feeling, Feeling	Pressure, Pressure, Torque	A2	Feeling	Position
4.2 Wait until max momentum has reached	static	P1	Finger	B1	Arm, Hand	A2, A1	Feeling, Feeling	Pressure, Pressure	A2	Feeling	Position
4.3 Remove finger from trigger	trans	P1	Finger	S5	Arm, Hand	A3	Feeling	Pressure,	A3	Feeling	Position
5. Remove tool from screw head	trans/ rot	M1	Arm, Hand	0	0	A2/ A1	Eyes, Feeling	Position, Force	0	0	0

Multiple co-occurring factors were responsible for the finding that an action level contains too specific information for the task abstraction process. The first point to be mentioned is that a more detailed level of the process analysis led to lower confidence of the analyst with respect to achieving realistic results. Actions are most likely performed with variability arising from human errors. There is no guarantee that the worker actually performs the task based on an action level plan. Even if the worker would grasp the wrong tool, the action level would be corrupted. Consequently, when analysing such a task, an ideal world scenario is being created by the analyst, which highly unlikely to be fulfilled by an operator. Therefore, presenting such a level of detail is at least questionable. The findings were also supported by the time aspect of an SGT analysis. To reduce a possible task down to an action level is very time-consuming due to the level of detail required as well as the consideration of an ideal action scenario.

In addition to that, without attribution of tasks through the tool with the perception senses used, a functional representation of the production process is difficult. The attempt to cluster the task purely based on a combination of actions has led to very noisy and unstructured results with almost no meaning for both, a generic statement and for automation. To avoid a congruence bias as to test the hypothesis solely in a direct manner, the possible alternative hypothesis with regards to the level of process analysis detail has been investigated.

The test of different levels (process, task, operation, action) led to the functional task abstraction using the operational level. Process and task level do not provide sufficient detail, whereas the action level presented too much detail. As a consequence, a decision was made to extract the task information based on an operation level. The knowledge influenced the consecutive domain of process representation and modelling.

6.2 Process Representation and Modelling Domain

To validate the process function abstraction against the current analyst approach, five different case studies were considered, which are presented in Appendix B. The aim is to compare the clustering algorithm identifying specific functions with solutions created by automation experts (IDEF0). The idea behind the IDEF0 instrument is the hierarchical and functional representation of processes based on experts' beliefs. The IDEF0 are carried out in a determined and standardised way [328], [329]. The following section compares clustering results to the classically identified process functions and both mechanisms will be compared with the established solution. The individual sections will present the results for each case study demonstrating a percentage distribution of attributes among different process functions based on the clustering results of the operations. Therefore, Table 6-3, for example, will display the functions on the left-hand side and the appearing manufacturing process attributes on top of the table. The results show the percentage distribution of different attributes within the individual process function. Rather than a limited method for one purpose, the clustering approach may be adapted to different areas of human factors and build upon previous contributions. In the thesis, manufacturing attributes are abstracted to inform the decision process. However, different classifications may be used (for example categorisation of perception senses, variability influence diagrams, etc).

6.2.1 Welding

The first case is the welding process. As can be seen in the following figure, Sanchez-Salas has identified 5 different functions presented in the IDEF0 diagram [141]. Those 5 different automation functions have been displayed in Figure 6-1.

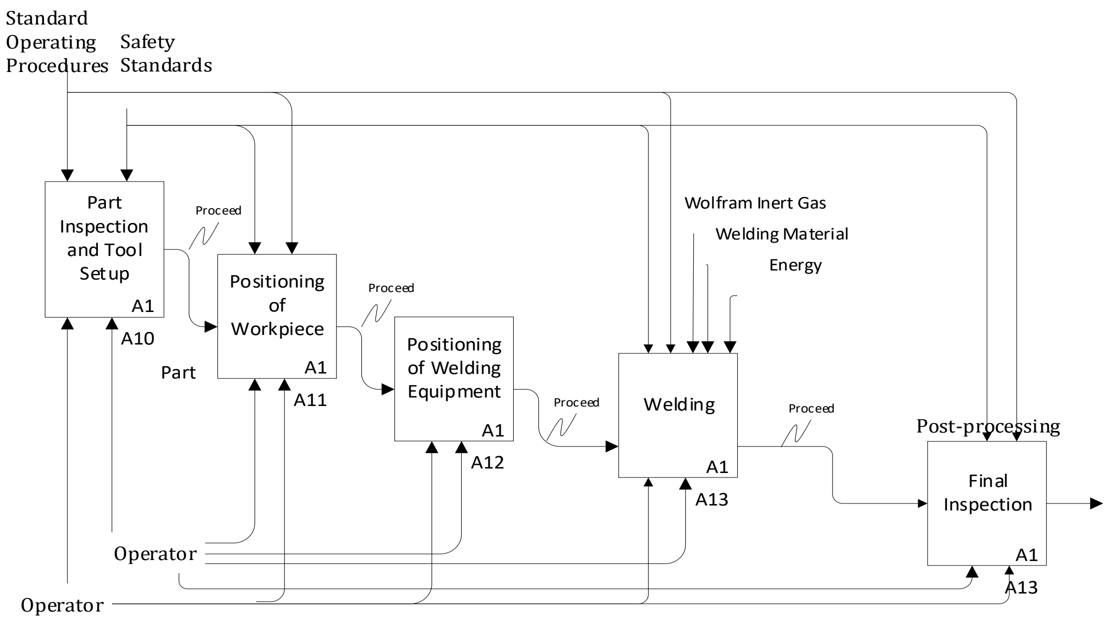


Figure 6-1: Case Study Welding - IDEF0

A solution for the same process is obtained from the clustering analysis by the decision support tool. The tool created four different functions as summarised in Table 6-3.

Table 6-3: Case Study Welding - Clustering

Process Function	*Joining Through Welding*	*Cutting with geometrically undefined cutting edge*	*Pick and Place*	*Tool Changing and Setup*	*Visual Perception Texture*	*Visual Perception Distance*	*Automation Function*
1	100%	0%	0%	25%	100%	100%	Welding
2	0%	100%	0%	0%	0%	0%	Grinding
3	0%	0%	100%	0%	0%	0%	Pick & Place
4	0%	0%	0%	75%	0%	0%	Tool Changer

However, the clustering algorithm included welding (100% of the attributes accumulated) and inspection (100% for texture and distance) in one function and added a grinding process as an additional function (Function 2). Within the manual operation list, the tip of the welding tool had to be ground. The presented step does not occur in the actual solution automation solution. The actual solution consists of welding, inspection, tool setup, as well as pick and place. Otherwise, the prediction of the welding functions from the clustering algorithm would have been accurate. The IDEF0 method divided the process functions into a repetitive pattern of tool preparation and setup. Although, the method ignored the visual inspection as well as grinding the welding tip.

6.2.2 Grinding

The second case study, a grinding process, was manually abstracted into 5 different functions by research engineers in IDEF0 [231] and, in contrast to that, clustered into 4 automation functions. The research goal was to enable a grinding that follows the part geometry and independent of the part achieves a specific tolerance. The five main functions of the system recommended by the expert presented were:

i. Identify and Locate Defect on Surface with 2D/3D Vision System
ii. Adapt Abrasive Belt Feed Rate in Real-Time
iii. Force/Contact Control Between Part and Abrasive Tool via Force/Torque Sensor
iv. Visual Inspection

Based on the initial recommendations, the IDEF0 diagram subsequently presented (see Figure 6-2) has been produced.

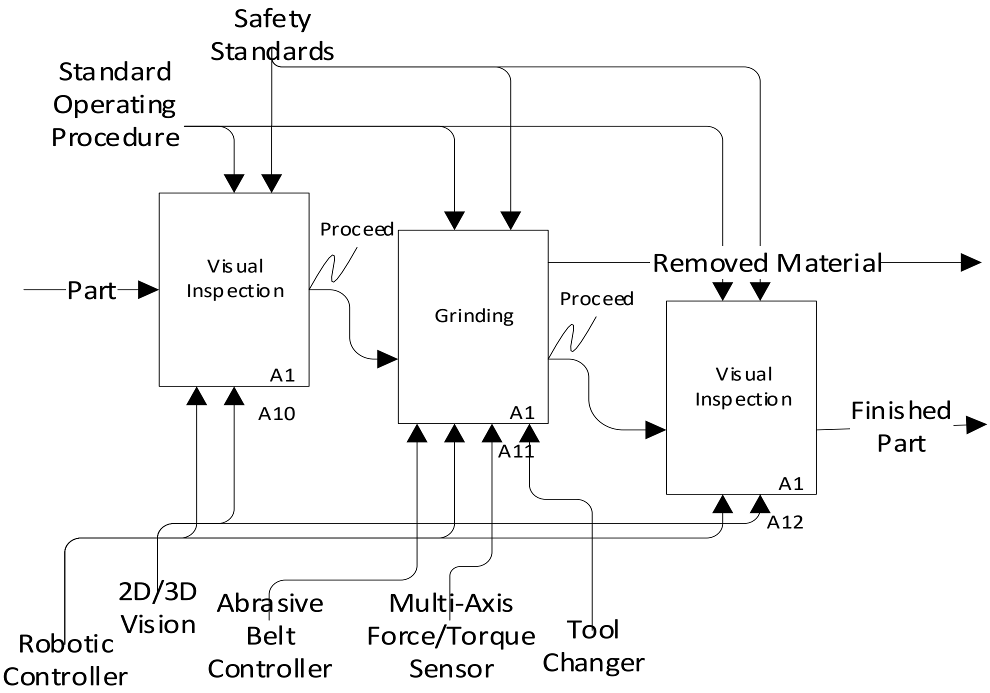


Figure 6-2: Case Study Grinding - IDEF0; Initial Recommendations for Automation by Kalt, p.111 [231].

Clustering proposes a different solution to that recommended by Kalt [231]. The algorithm extracts four different functions from the operation data (Table 6-4). Firstly, a function that combines “cutting with a geometrically undefined cutting edge” (100%) with a tactile force perception (100%) and a tool changing system (20%). The second separate function contains a visual perception system of the part surface/texture (100%). Turning the blades in between the grinding processes has resulted in a separate “pick and place”- function (pick and place attribute to 100% accumulated in process function 2). The last function of the clustering leads to a tool changing operation (remaining 80%).

Table 6-4: Case Study Grinding – Clustering

Process Function	*Cutting with geometrically undefined cutting edge*	*Visual Perception Texture*	*Pick and Place*	*Tactile Perception*	*Tool Changing & Setup*	*Automation Function*
1	100%	0%	0%	100%	20%	Grinding
2	0%	100%	0%	0%	0%	Visual Inspection
3	0%	0%	100%	0%	0%	Pick and Place
4	0%	0%	0%	0%	80%	Tool Changer

The automation system consisted of a grinding application (abrasive belt) and a separate gripper containing the force/torque sensor. In addition to that, a visual inspection application was suggested, but not implemented for part inspection. The finding leads to the following conclusions for the grinding project. The clustering application has accurately predicted 3 of the 4 functions that have later been implemented. The tool changer was not needed as the robotic solution did not require a change of the abrasive belt due to the high accuracy of the automated grinding process. At the same time, the tactile feedback of force and torque was allocated at the gripping system rather than the grinding applications. The underlying reason is the commercial availability of grippers containing force and torque feedback (etc. Schunk Gripping Systems). Nevertheless, the predictions of the clustering algorithm are slightly more accurate in terms of system design, whereas the expert presents a more detailed perspective on automation tasks at the beginning of the automation process.

6.2.3 Drum Beater Winding

The drum beater winding process is manually translated into 3 different functions (Figure 6-3). The functions were identified as the winding of the thread around the beater. The second identified function is to secure the winded thread at the top and bottom with a stitching process. At the end of the process, the experts have identified a third process responsible for a pattern stitching around the beater.

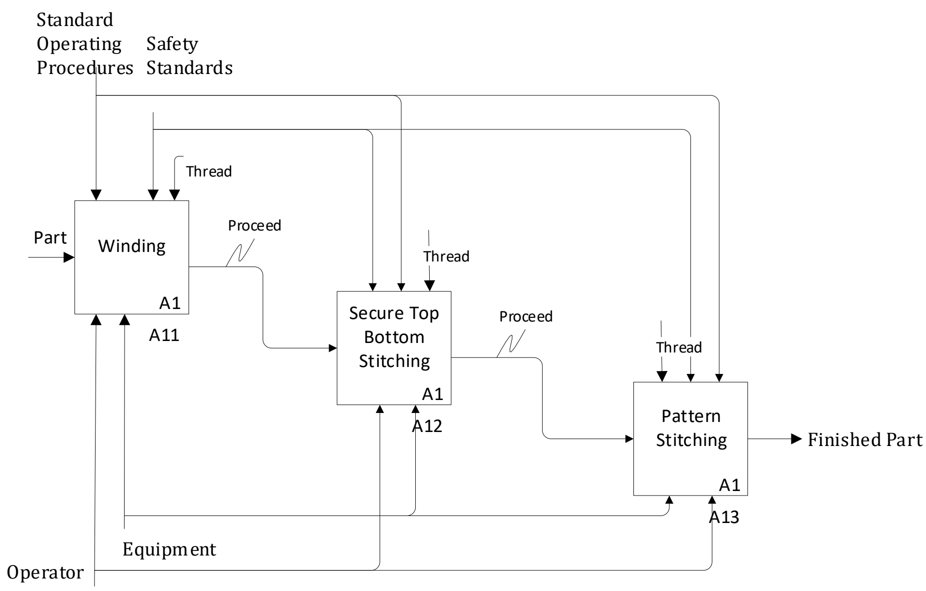


Figure 6-3: Case Study Beater Winding - IDEF0

The algorithm produces three functions too (see Table 6-5). The first function contains textile joining (100%), visual perception of the texture (100%), and cutting with a geometrically defined cutting edge to cut off the thread (100%). The function can be interpreted as the sewing function of the process. The second function contains the attribute for pick and place (100%) extended by a measuring device for the counterforce based on tactile measurements (100%). The function represents the winding process of the thread. After the winding process is finished, the operator covers winding gaps in the pattern. Covering the gaps results in a visual system of the first function to identify the texture and correct the errors. To switch between both functions, a tool changer has been identified in function 3.

Table 6-5: Case Study drum Beater Winding - Clustering

Process Function	*Textile Joining*	*Pick and Place*	*Tool Changing*	*Visual Perception Texture*	*Tactile Perception*	*Cutting with geometrically defined cutting edge*	*Automation Function*
1	100%	0%	0%	100%	0%	100%	Sewing
2	0%	100%	0%	0%	100%	0%	Customised Project
3	0%	0%	100%	0%	0%	0%	Tool Changer

The actual solution is almost identical with the clustering function, but with one exception. In the automated process, the tool changing would take place manually combined with a visual inspection. The clustering algorithm has combined the visual inspection and the winding process. The experts have identified three process functions, which are the winding process, the top/bottom security stitching process, and the pattern stitching process. The problem is that experts tend to neglect the tool changing process as part of the automation process. If different mechanisms are required, a tool changing process is necessary, but often neglected by the experts.

6.2.4 Threaded Fastener Assembly

The results obtained from both the expert and the algorithm for the threaded fastener assembly process as a fourth case study are similar (see Figure 6-4 and Table 6-6). The expert identified approach and alignment clustered by the tool within the pick and place process. The process included 100% of the pick and place attributes as well as 50% of the attributes responsible for the visual determination of a distance. Additionally, an 80%-share of the visual tool to recognise an object shape was attributed to function 2. This is since the task needs to identify the target hole, the related screw (visual perception of distance and object), grasp the screw (pick and place) and deliver it to the according position. The fastening function (Function 1) accumulated the remaining visual shares (distance and object shape) and 100% of the ‘pressing in and on’ attributes. The pressing in and one attributes correspond with the fastening mechanism as well as the visual capability of aligning and approaching the target position. The remaining percentages were connected to the tool changer. The tool changer is used to switch from a pick and place to an assembly process.

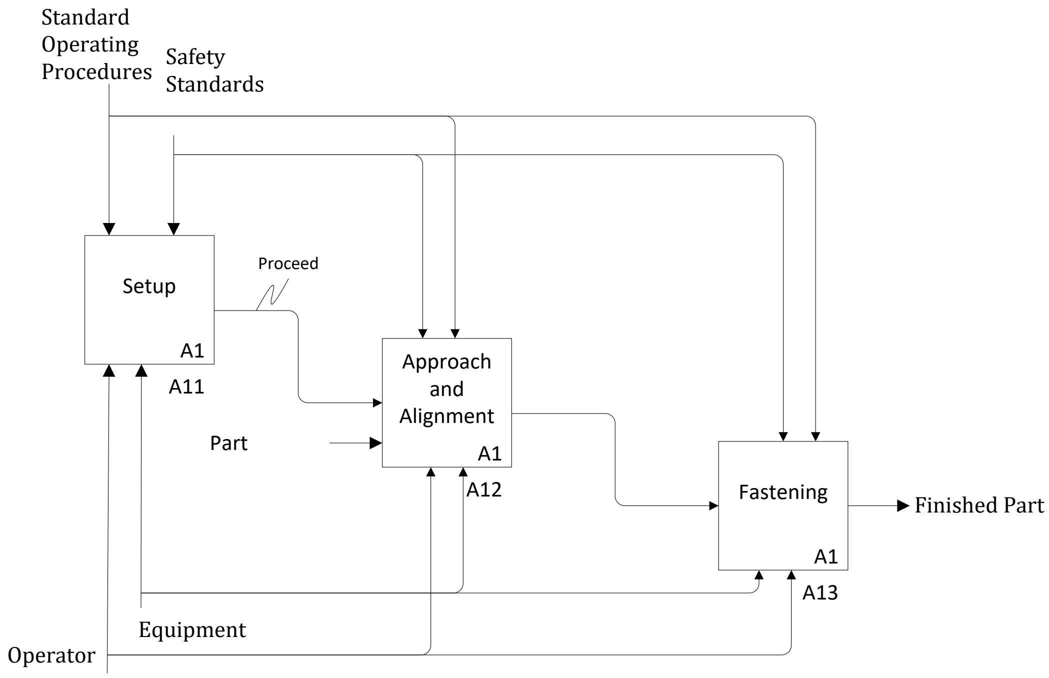


Figure 6-4: Case Study Beater Winding – IDEF0

The insertion task of the expert was labelled by the tool as part of the auto-fastening process. However, instead of adding a tool changing function, the expert introduced a torque control function. Even though the expert identifies the key challenges, the individual function is not necessarily represented correctly but focuses on describing the required system capabilities in terms of sensorial/programming challenges. An evaluation of those challenges is separately conducted in the second part of the tool. Nevertheless, the tool changing capability is again missing in the expert solution.

Table 6-6: Case Study Threaded Fastener Assembly - Clustering

Process Function	*Pressing in and on*	*Pick and Place*	*Tool Changing & Setup*	*Visual Perception Distance*	*Visual Perception Object Shape*	*Automation Function*
1	100%	0%	0%	50%	20%	Fastening
2	0%	100%	0%	50%	80%	Pick and Place
3	0%	0%	100%	0%	0%	Tool Changer

The manufacturing process considered next is a deburring process.

6.2.5 Deburring

Lastly, the deburring process has not been automated yet. A possible reason was the complexity of the automated solution. The complexity is not specifically indicated by the manual process abstraction. The manual process abstraction identified 2 different functions (see Figure 6-5). The functions are a selection of the appropriate tool and inspection, as well as the deburring process. These functions are executed in loops because of the large number of features on the product.

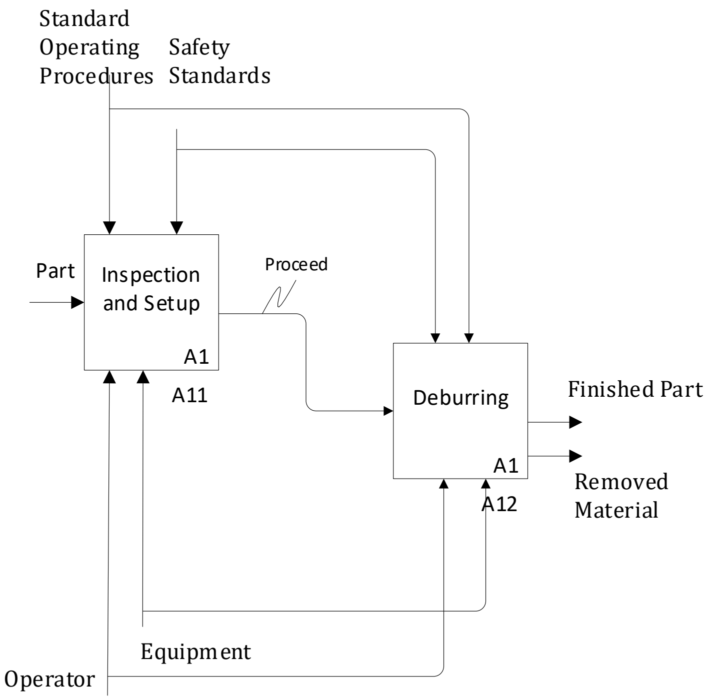


Figure 6-5: Case Study Deburring – IDEF0

The algorithm indicates that a complex tool is needed requiring a visual-haptic process control and a decoupled visual inspection process (Table 6-7). The two automation functions require in-depth knowledge and indicate a high complexity from a programming perspective. The clustering algorithm presents a more complex solution than the manual solution having identified 4 functions.

Table 6-7: Case Study Deburring - Clustering

Process Function	*Cutting with geometrically undefined cutting edges*	*Tactile Perception Texture*	*Tactile Perception Object Shape*	*Visual Perception Object Shape*	*Visual Perception Texture*	*Visual Perception Distance*	*Tool Changing & Setup*	*Cleaning*	*App*
1	100%	0%	0%	20%	20%	100%	0%	100%	Grind
2	0%	100%	100%	40%	40%	0%	0%	0%	Visual-Tactile Control
3	0%	0%	0%	40%	40%	0%	0%	0%	Visual Control
4	0%	0%	0%	0%	0%	0%	100%	0%	Tool Changer

6.2.6 Process Representation Summary

This section has compared the results from an analysis of the human task abstraction process and the clustering algorithm. The process represents the translation of information from the task analysis and human factor domain to the decision-making for automation domain. Without the systematic transformation of task information, the uncertainty of decision factors for the overall task might be significantly higher. Due to the length of the case studies, only key parts of the results are presented to discuss the findings (see Table 6-8). The results prove that the clustering algorithm achieves its goal of a functional task abstraction and, in some of the cases, is more accurate than the initial IDEF0 prediction of the automation experts.

Table 6-8: Comparison of Clustering and IDEF0 - Results Summary.

Process	*Manual Abstraction (IDEF0)*	*Clustering Algorithm*	*Actual Solution*
Welding	**5 Functions** [141] (Preparation = Tool Setup, Positioning, Positioning 2, Welding, Inspection)	**4 Functions** (WIG Welding + Inspection, Grinding, Pick and Place, Tool Changer)	**4 Functions** (Welding, Inspection, Tool Setup, Pick and Place)
Grinding	**5 Functions** [231] (Part Geometry Following, Visual Detection, Belt Feed Rate Control, Grinding & Force/Torque, Visual Inspection)	**4 Functions** (Grinding with Force/Torque Sensor, Part Inspection, Object Manipulator, Tool Changer)	**2 Function** (Auto-Grinding + with Manipulator Force/Torque Sensor and Gripper, Part Inspection)
Drum Beater Winding	**3 Functions** [Internal] (Winding, Secure Top Bottom Stitching, Pattern Stitching)	**3 Functions** (Stitching, Customised Process = Winding, Tool Changing	**3 Functions** (Stitching, Winding, Tool Changing)
Threaded Fastener Assembly	**3 Functions** [232] (Approach and Alignment, Fastener Insertion, Torque Control)	**3 Functions** (Auto-Fastening, Pick and Place, Tool Changer)	**3 Functions** (Auto-Fastening, Pick and Place, Tool Changer)
Deburring	**2 Functions** [141] (Selection of Tool = Tool Setup, Removing = Deburring)	**4 Functions** (Grinding, Visual-Haptic Process Control, Visual Inspection, Tool Changer)	**Not-Automated** (-)

One of the principal differences is that experts tend to label process functions based on the individual perceived challenges of the automation problem. As a result, the experts may not always be able to accurately describe the later system design and different experts may reach different conclusions. The clustering algorithm takes a data-driven approach and, therefore, fails to disregard functions that may not be needed. However, the approach is highly repetitive and demonstrates its functionality throughout all the presented case studies in predicting later functions of the system design. The goal, however, is not to predict the automation feasibility at this stage. This will be performed in later parts of the decision support tool. Generating the results takes around 12 minutes. Two minutes are spent on the attribution process of the HTA structure and another 10 minutes are needed for clustering calculations. Considering the difficulty of system design predictions, 12 minutes may be considered acceptable. Additionally, the approach does not require full expertise in automation, but knowledge about the manual production process is sufficient.

The following section will present the result from the decision-making process based on the input of the Manufacturing Technology Centre (MTC).

6.3 Decision-Making for Automation Domain

This section presents the results arising from the conceptual framework and the related realisation. The decision support tool according to the industrial partners' input will be validated in different ways. One partner has contributed to the expert elicitation process. The MTC experts focused on the technical perspective of the decision-making process.

The MTC's motivation is derived from the strive to provide feedback for customers of the centre to assess the technical difficulty of automation projects, which is currently done by the lead engineers. The related experts have contributed to the presented work. To assess the Bayesian Network in a fair and independent manner, the thesis adopts a Validity Testing Framework for Bayesian Belief Networks based on Pitchforth and Mengersen [235]. The key aspects of the framework are a validation of the following main aspects of a Bayesian Network:

i. Nomological Validity
    a. Is the Bayesian Network set in the appropriate context in literature?
    b. Are the themes nomologically adjacent/distal?
    c. Are there antitheses between parameters?
ii. Face Validity
    a. Does the model show similarities to the literature?
    b. Discretised enough to reflect expert knowledge?
    c. Parameters reflect expert expectations?

iii. Content Validity
   a. Are all factors considered?
   b. Are only relevant factors considered?
   c. Does the selection of parameters reflect all known possibilities from expert knowledge and literature?

iv. Concurrent Validity
   a. Is model structure identically modelling a theoretically related construct?
   b. Comparison model discretised in the same way as a used model?
   c. Input nodes match parameters of the comparison model?

v. Convergent Validity
   a. Comparison between dependencies in similar research?
   b. Independencies in similar research areas?

vi. Discriminant Validity
   a. The difference of model structure to nomologically distant model?
   b. Expert Validation (Correct Model)?

vii. Predictive Validity
   a. Model behaviour predictive (Case Study)?
   b. Are individual node results predictive?
   c. Is the model sensitive to parameters identified as important?
   d. Qualitative feature and behaviour of model observable (+ extreme model behaviour)?

As part of the results, a comparison of the decision support tool with other network sampling algorithms created by a commercial Bayesian network tool called GeNIe 2.1 will be carried out to ensure the mathematical validity of the presented work. Prior to a detailed explanation of the critical success factors and related categories, a reminder for the restricted information to be published shall be given. To validate the decision-factors of the experts later, the following chapter will prior to the experts responses collect decision-factors from the literature. This may support the result validation.

6.3.1 Identification and Quantification of Critical Success Factors for the Framework

This subsection presents the methodology according to the identification and quantification of critical factors for the framework. The subsection summarises the collected literature sample and investigation methodology (see Figure 6-6). Starting points are two databases containing relevant papers in the investigated research domain. The papers are then manually evaluated and by use of a text mining tool. Based on text mining, an understanding of the quantitative relationships of critical success factors in the accumulated literature is established.

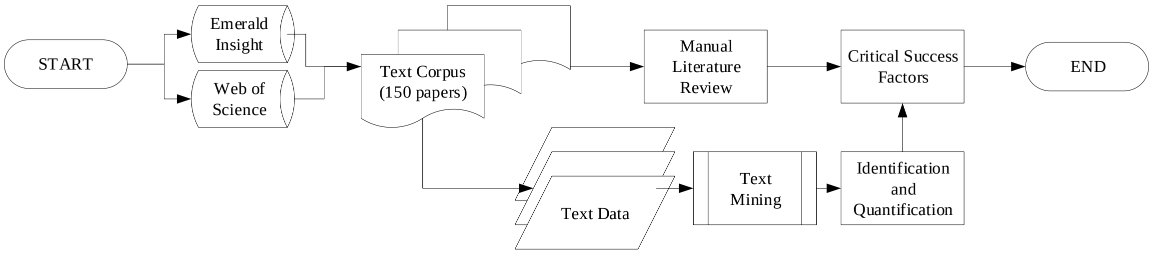


Figure 6-6: Applied methods to extract knowledge from the existing literature.

In one of many existing definitions, automation is defined as a hardware and software system (or device) that executes a manufacturing function previously accomplished by humans. [152]. Deciding on which process to automate is confronted with a significant number of critical success factors [128].

A. **Approach**

Most of the current literature uses expert knowledge to justify a catalogue of objective and subjective criteria. The following study uses the Wordsmith Tool (Version 7.0) to identify the criteria based on a paper sample and display reliable quantitative results. The previous approaches used expert opinions and qualitative studies to rate specific factors, see [5], [24], [176]–[178], [180], [182], [184], [186]–[189], [127], [190], [191], [194], [196], [237]–[242], [131], [243]–[252], [165], [253]–[262], [167], [263]–[272], [169], [273]–[282], [171], [283]–[292], [172], [293]–[295], [174]. The adopted approach will allow to quantitatively justify the importance of factors by determination of different frequencies within the literature body.

B. **Evaluated Literature**

To identify the critical success factors, the first action carried out was the collection of a suitable literature corpus of papers for the last 30 years. During this time, simple mechanical automation has evolved over computer-integrated manufacturing towards more intelligent systems. An investigation will, therefore, demonstrate, which critical success factors remained important over all technological developments. The sample covers 150 papers and is compiled from two different databases using the search criteria as shown in Table 6-9 and a manual review of abstracts. The intention of the chosen sample was to include a representative cross-section of all the relevant aspects of the automation implementation process. Hence, the selected corpus includes strategic papers, operational process papers as well as papers dealing with the selection of technologies. The databases are selected with the aim to gather representative literature within the mentioned research area. Although the sample is not exhaustive, the author contends that a representative corpus is collected due to the cross-database search functions provided by the sample databases. After the keyword search, a manual selection of automation implementation related papers has been executed.

Table 6-9: Literature search terms and databases.

Search words	**Database**	**Cross-database search**
Automation, Manufacturing, Technology Selection.	Web of Science	Yes
Multi-Criteria Decision-Making, Manufacturing, Technology Selection.	Web of Science	Yes
Selection of Automation Projects.	Web of Science	Yes
Operations Process Management, Automation, Manufacturing.	Emerald Insight	No

The identification of suitable literature leads to the approach to identify and quantify critical decision factors.

C. Critical Success Factors Identification and Quantification Methodology

A manual approach is applied to identify the most frequently used success factors and evaluation criteria in the collected text corpus. The results of the manual annotation are compared to those of a text mining tool (WordSmith Tool v7.0). The text mining program is used to extract success factors from the literature to ensure manually identified frequencies are comparable (see Figure 6-7). The approach does not rely on the opinions of individual experts but investigates the underlying consensus and trends reported in the literature.

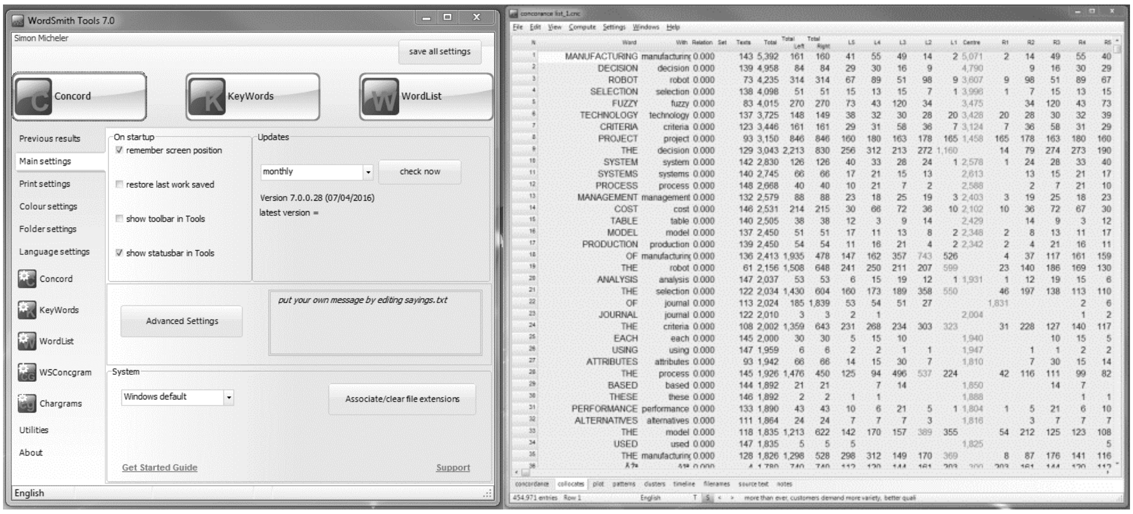


Figure 6-7: Wordsmith Text Mining Tool

For the text mining approach, the selected papers are converted from PDF into text files. The first step is to create a wordlist, which contains all the mentioned words in the texts. Avoiding a collection of meaningless words, a stopword list is used to force the program to ignore such words (for example “and”, “or”, “the”). The lemma list is created to find a collection of root words (for example costing, cost). The program presents a list of words and their frequencies as well as the corresponding number of documents they are mentioned in. The list is separated into two parts: (i) to identify the research areas and (ii) to show the different success factors. The separation provides the basis for a cluster analysis defining relations based on root-word co-occurrences.

However, the reader should notice that the method only extracts new relations and orders. The approach does not identify new concepts. The adopted approach gives an indication of the most frequently mentioned factors, which is expected to be indicative of their importance. However, new knowledge will be added in the second part. The following subsection describes the main results of the corresponding analysis.

D. Findings

The first results, which are presented in Figure 6-8, compare the total word frequency share within the literature with the distribution share of a word within all the literature. The gathered information shows three different meanings.

The three meanings are i) the importance of a word in the research area, ii) the distribution of a word in the whole area, and iii) the distribution and frequency in order to cluster words into research domains.

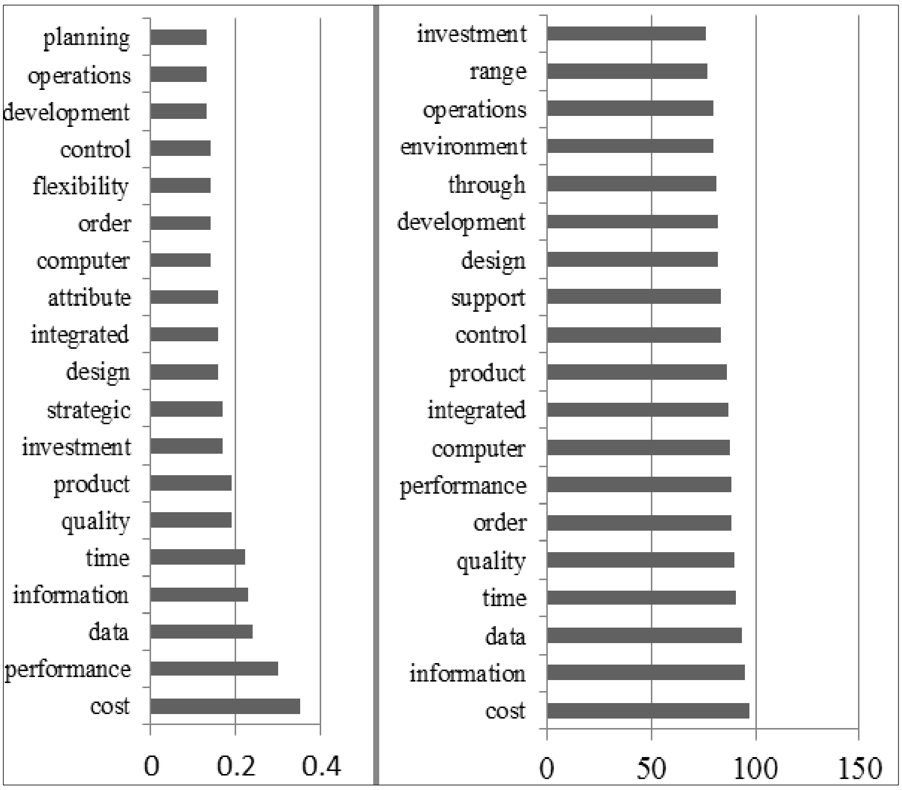


Figure 6-8: Total word frequency share within texts (le.) and share of texts containing the specific word (ri.), both in percent.

First of all, the results of the one-word frequency analysis show that the word *cost* plays an important role in almost every paper and, at the same time, displays the highest frequency of all the identified factors. However, the word *investment* is not used in the same way as the word *cost*. The result indicates a possible research area related to the word investment, which appears often, but is not equally distributed among all the papers. Furthermore, the data show evidence that data, time, quality, information and performance have a significant influence on the implementation process. From a global perspective, the findings might indicate the existence of two different perspectives. One perspective covering the financial aspects of the automation system, another introducing a technical perspective on the automation implementation.

To shed some light on the existing clusters, another investigation examined the co-occurrence of factors to cluster the results based on the likelihood of simultaneous appearance. To avoid confusion, the work will not mention clusters, which have previously been used as a search term for the collection of the literature sample. As a consequence, the clusters taken into consideration can be seen in the following Table. The complete list of clusters can be seen in Table 6-10. The table shows the cluster names and their fields of interests as well as the citations of the literature a specific cluster appears in. Clusters related to a natural occurrence within the texts, like ‘computer integrated manufacture’ have been excluded.

Table 6-10: Important Identified Clusters from Literature

Cluster name	Literature	Field of interest
load capacity repeatability	[24], [167], [186], [188]–[191], [194], [252], [255], [257], [261], [168], [267], [273], [277], [279], [285], [288], [296]–[298], [169], [170], [172], [177], [179], [181], [184]	Technical
load capacity velocity	[167], [169], [255], [257], [260], [267], [273], [288], [296], [297], [299], [174], [177]–[179], [182], [188], [190], [252]	Technical
cost load capacity	[168], [170], [255], [257], [277], [279], [172], [180], [182], [189], [190], [194], [242], [252]	Technical
information technology	[24], [127], [285], [289], [291], [295], [297], [299]–[303], [186], [188], [191], [238], [239], [271], [274], [282]	IT
production cost	[255], [277]	Economical
investment decision	[168], [182], [194], [252], [255]	Fincancial

The research area can clearly be separated into at least four different fields of interests. In contrast to the fact that the cluster *robot selection* is not used within literature search for the samples, the particular cluster appears most of the times in a high frequency with more than 400 appearances. In addition to that, the grouping shows a high number of different clusters, generally related to a limited and technical point of view (see Figure 6-9). Another cluster, which can be identified is the *information technology* cluster. As one could notice before, information technology is one of the most important aspects of automation. The cluster analysis supports the result of the word frequency statistic. Two different clusters have been identified. The first cluster can be seen as a *production costing* cluster taking many different costs into concern, whereas the *investment* cluster seems to focus widely on financial considerations and models.

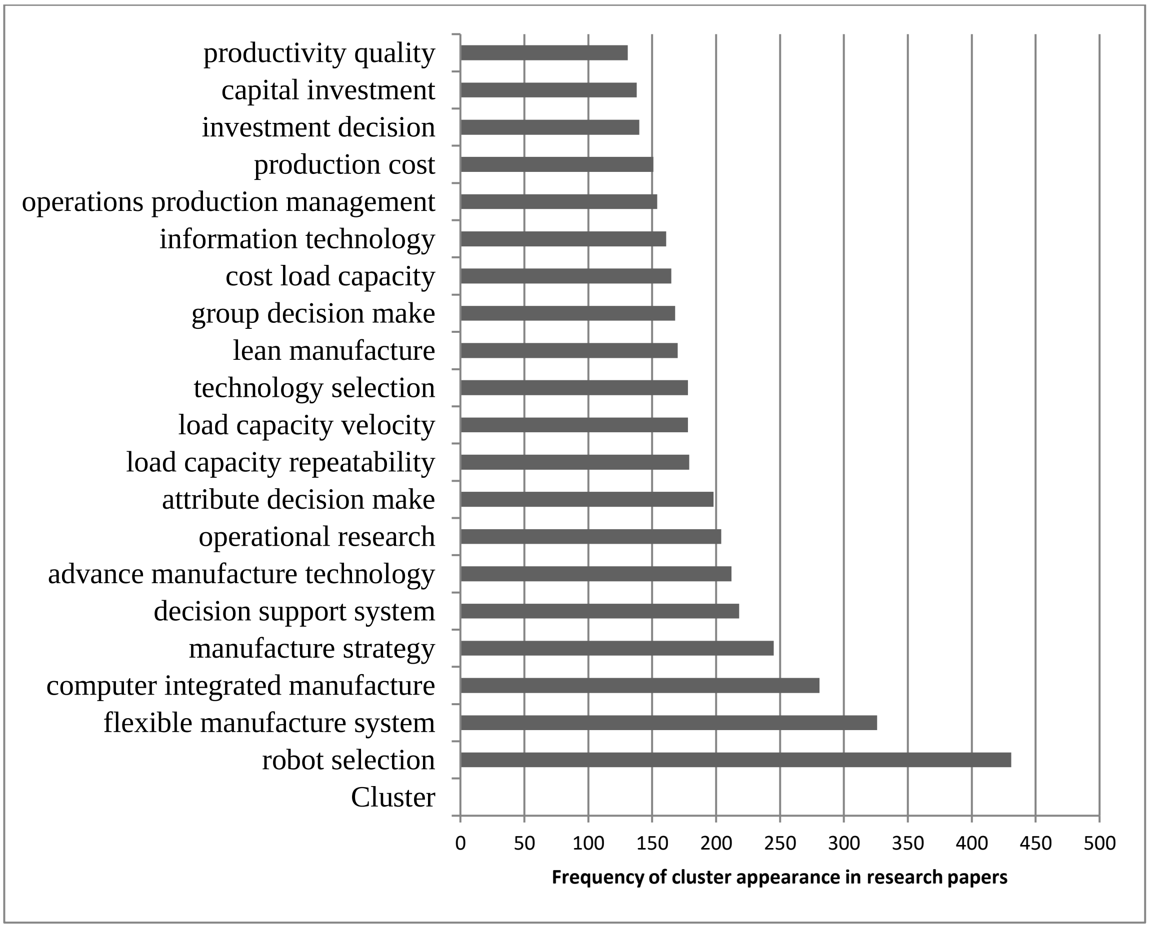


Figure 6-9: Research area cluster frequencies within the literature

Generally, the analysis of the literature regarding the implementation of automation leads to the conclusion that the domain is appropriated by a technical perspective. On one hand, there appears to be a great interest in the costing of automation. On the other hand, fewer papers in the sample consider the total costs of ownership and life-cycle costing. The discoveries might be indicating issues related to the application of costing for implementing automation. As the problem to cover the whole problem of automation adoption remains, a more practical approach towards the implementation of automation should be considered. The most important factors seem to rely on factors arising from both, a technical perspective and cost perspective. However, the technical factors seem to consider primarily robotic aspects rather than deriving technical conclusions from the manual task. One of the most important remaining research questions is how to translate the knowledge of critical success factors into a decision model. The translation seems to be a barrier to preventing possible automation implementation for manufacturing. And yet, the quantification implies automation decision-making relies heavily on a technical perspective.

This study has presented a quantitative perspective on the automation literature and will help to validate the expert opinion. Commonly implied is that automation faces difficulties confronted with smart technologies. The implication might arise since evolving from standard automation is achieved by increasing the capabilities of dealing with variabilities and, therefore, issues with new technologies arise. The related technologies are called smart technologies in the context of industry 4.0.

6.3.2 Technical Perspective

The expert workshop was conducted at the Manufacturing Technology Centre (MTC) site in Coventry. The workshop was attended by four automation experts divided into four individual teams. The experts' affiliations are related to the implementation of novel manufacturing technology for process automation. Attending were lead engineers and automation engineers. In the first stage, the experts were looking into the extraction of expert knowledge by collecting important decision factors. The participants drew an influence diagram collectively. Next, a discussion of the results was carried to merge the view of the participants. The consolidated picture was used to interview the four attendants about the mathematic relationship of the network structure to design the Belief Network. Due to the sensitivity of data, the numerical results cannot be displayed. The data presented in the graphic will be desensitized (see Figure 6-10).

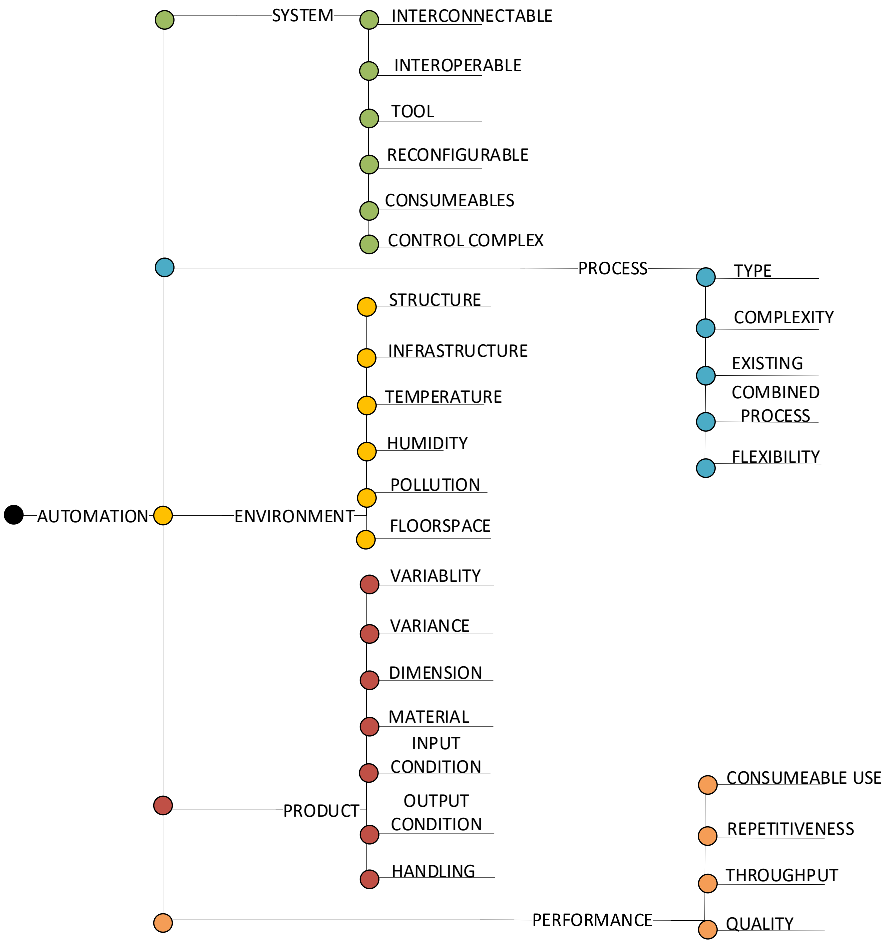


Figure 6-10: Desensitised Technical Bayesian Network Structure

The following step will now validate the entire created model based on the previously introduced validity model.

A. Nomological Validity and Face Validity

To validate the technical network nomologically, it has been assessed whether the network is set in the appropriate context within the literature. Based on the analysis, conclusions to whether an antithesis has been detected can be drawn with respect to the accumulated knowledge. Therefore, the literature and extended study will be considered.

Analysing the technical network, one can understand that the technical automation domain was divided by the MTC experts into five different categories, which are the system, the process, the product, the environment, and the anticipated performance. Among the research output to date process, product, and the environment are mainly covered by the task complexity domain Chapter 2.1.2. The performance factors are represented by the technology selection domain (see Chapters 2.3.3) and the system's perspective is taken by the extended study of smart technologies and systems in the context of Industry 4.0 (see Chapter 4.1).

The system perspective is generally reflected in section 4.1, where barriers to the introduction of smart technologies are presented. As section 4.1 presents, inter-connectivity (integration of communication technologies, integration of data processing technologies, data processing capacity) are issues reported by the industrial experts arising from the internet of things and intelligent automation. Simultaneously, the experts have identified interoperability as important (compatibility with existing machines) and control complexity (see section 2.1.2) and reconfigurability (new industry standards, the ease of implementation, self-adaptive factory).

From a product and environment perspective, most of the factors the MTC experts have presented equally arise from the related research domain (task complexity) presented in the literature review. Angel Sanchez-Salas (Table 2-2) has identified numerous factors that are mentioned by the experts in relation to the product perspective (Uncertainty, Presentation Heterogeneity, Inconsistency ~ Variability, Variety/Diversity, Number of Products ~ Variance, Presentation Heterogeneity ~ Handling, Specification/Structure ~ Material, Dimension) [141]. The environmental perspective is addressed in terms of the structure (Structure). Liu et al. have identified the origin of issues related to the input and output condition similar to the product- factors by the MTC (Input and Output Condition) as well as from an environmental perspective related to the structure of the process (structure, unstructured guidance) [97]. The process factors are reflected by the task complexity research in terms of the complexity (~ number of information cues, number of operations, difficulty) as well as by the investigation of Liu et al. in terms of the combination of processes (~ heterogeneity, repetitiveness) [97]. The performance factors are mostly represented by the technology selection literature for introducing automation. Among a list of the most important factors for an automation system (Figure 6-8) are quality, time as well as from a technical perspective (Table 6-10) repeatability. Also mentioned in the domain is flexibility, which has been addressed among the process factors in the technical Bayesian Network.

The overall perception gained from the comparison is that no antithesis was found among the critical success factors in comparison to the current research environment. The model shows strong similarities with the research domain and reflects on the topic from different technical perspectives.

B. Content, Concurrent and Convergent Validity

In terms of the content, concurrent and convergent validity of the related factors, a conclusion whether the experts have created a holistic picture of the automation reality is difficult. Naturally, a possibility of falsely included factors remains and forgotten/underestimated factors within the Bayesian Network. Due to the probabilistic structure arising from the expert network, an opportunity to identify weak representations within the Bayesian Network might arise as a result of an analysis of the dataset.

For the collection of the MTC data, the DELPHI-method has been applied for the structural design to collect individual responses by the experts and a group reflection on the produced results. The individual expert input of the prior probabilities was additionally investigated using correlation and covariance as expert assessment. Given the limited access to experts in the field and the sensibility of the extracted data, confidence is present that the belief network expresses the experts' opinions sufficiently. The results of the investigations will be displayed in the following sections.

C. Predictive Validity

The following section investigates the predictive validity of the created Bayesian Belief Network. Part of the investigation is an expert validation, the individual node behaviour prediction and the overall model behaviour prediction. The overall aim is to validate whether qualitative features and behaviours of the model are observable as well as how those features respond to real case studies.

a. Expert Validation

The statistical inputs of the experts will be compared with each other to verify the individual expert was drawing similar conclusions about individual results. After the network was created using the DELPHI-method, the verification of the inputs is the next logical step resulting from the individual interview sessions. Two different factors will be considered. The correlation among the expert responses (does one answer behave similarly to the other answer) and the covariance (does an expert answer change if changing for other experts). A combination of both factors allows investigating the correlation from two different dimensions (see Table 6-11 and Table 6-12). Table 6-11 shows the correlation matrix. Among all the experts, a highly significant correlation (2-tailed, significant at the 0.01 level) has been detected. The correlation designates that the expert results are significantly similar to each other. The highest similarities are indicated between expert 1 and expert 3.

Table 6-11: Technical Input Expert Correlation for Prior Probabilities.

Correlation among Expert Responses				
	Correlation Type	*Exp1*	*Exp2*	*Exp3*
Exp1	Pearson Correlation	1		
Exp2	Pearson Correlation	.775**	1	
Exp3	Pearson Correlation	.812**	.606**	1

Simultaneously, the covariance among the expert is high meaning a covariance almost identical to the covariance among the expert's own input probabilities (for example COV(Expert 1, Expert 1)=1046.3, COV(Expert 1, Expert 2)=916.4). The combination of results demonstrates the independence of those factors giving the input of the probabilities is unlikely.

Table 6-12: Technical Input Expert Covariance for Prior Probabilities.

Covariance among Expert Responses			
Factorial Differences	*Exp1*	*Exp2*	*Exp3*
ExpDiff1	1046.265		
ExpDiff2	916.3818	1334.937	
ExpDiff3	1011.701	852.7637	1485.2

The statistical analysis so far gives confidence that the experts share similar views on the prior probabilities among the network structure. The presented statistical numbers lead to the analysis of the Bayesian Network itself.

b. *Statistical Analysis of Bayesian Network*

The statistical analysis draws conclusions from a correlation between the factorial outcome and the different factors presented in the technical BBN (see Table 6-13). The case average correlation describes the correlation between the factors and the case average calculated beforehand. The average case, in contrast to that, calculates the correlation of the factors related to every individual case and concludes the average after. As can be seen in the network structure, the factors are principle divided into 5 different categories. The five categories are *product, environment, system, process*, and *predicted performance*. The reason a standard deviation correlation of the factors was included is due to the fact, that factors might have to take a specific value regardless of the influence towards the estimated intelligent automation success. The absence of such a value would reduce/increase the sample of the MCMC method and, consequently, reduce the number of cases (increasing the standard deviation). A case without health and safety just cannot exist. Even though the aspect has never been reported as a contributing factor, however, the uncertainty given a missing health & safety aspect is comparatively high.

The first category presented contains *product factors*. Within the product category, four factors correlated significantly with the average case results. The occurrence of variability and a product mix (variance) seems to correlate negatively with the intelligent automation probability of a process. Additionally, a suitable dimension of the product (not too large/small) and a good input condition seems to favour the automation of a process additionally.

Table 6-13: Statistical Analysis of the Bayesian Network after MCMC-Technical.

Factorial Correlation Between Factor and Outcome

Product	*Variability*	*Variance*	*Dimension*	*Material*	*Input Condition*	*Output Condition*	*Handling*
Average Case	-0.43038*	-0.43364*	0.484459*	0.314733	0.449526*	0.180453	0.006536
Case Average	-0.3966	-0.39967	0.446874*	0.290321	0.414265*	0.166341	0.005666
Standard Deviation	0.405442*	0.224921	-0.08408	-0.11074	-0.1664	-0.36452	-0.35774
Environment	*Floorspace*	*Pollution*	*Humidity*	*Temperature*	*Infrastructure*	*Unstructured*	
Average Case	0.002565	-0.27387	0.20396	0.236051	0.251197	0.184234	
Case Average	0.002837	-0.08075	0.059718	0.068544	0.077301	0.056233	
Standard Deviation	0.075802	0.526865**	-0.37502*	-0.46327*	-0.23974	-0.20859	
System	*Inter-connectable*	*Inter-operability*	*Tool*	*Re-configurable*	*Control Complexity*		
Average Case	0.067734	-0.02509	0.018954	-0.00655	-0.26875		
Case Average	0.020449	-0.00377	-0.00093	-0.00721	-0.05089		
Standard Deviation	-0.14618	-0.79726**	-0.15138	0.320647	-0.13566		
Process	*Type*	*Complexity*	*Existing*	*Combined Process*	*Flexibility*		
Average Case	0.25456	0.015747	0.513568**	0.603255**	0.526801**		
Case Average	0.238814	0.015246	0.481799*	0.564504**	0.494289*		
Standard Deviation	-0.36773	-0.41432*	-0.21835	-0.39505	-0.2469		
Pred. Performance	*Consumable Use*	*Repetitive*	*Through-put*	*Quality*			
Average	0.343973	0.675894**	0.415422*	0.462971*			
Case Average	0.34144	0.671111**	0.412462*	0.459681*			
Standard Deviation	-0.57139*	-0.61773*	-0.10454	0.06875			

* *correlation*
***significant correlation*

From an *environmental* perspective, the factors' impact on the final automatability does not significantly correlate. And yet, it should not be concluded on redundancy of factors. Most of the factors do not significantly correlate with the automation probability but might be correlating in a specific combination. An individual correlation factor might be low, but still high considering combinatorial correlations. The particular information cannot be easily obtained from the dataset due to the combinatorial possibilities of the Bayesian Network. However, the standard deviation correlation suggests, that the occurrence of humidity and temperature related issues is rare. Highly positive is the correlation between workspace pollution and the standard deviation. The results indicate that not many cases have been reported where the workspace was polluted. Therefore, the assessment of cases where pollution occurred is very difficult and drives the automation probability towards uncertainty.

A similar picture can be drawn related to the *system* perspective of intelligent automation factors. In terms of correlation with the automation probability, the system factors do not significantly correlate. However, the correlation of the interoperability with the standard deviation is very significant. If issues related to the interoperability have been reported, the impact on the standard deviation was highly negative. The findings are an indication of a rare case. Decreasing the interoperability of a process will significantly increase the intelligent automation uncertainty.

Another category identified by the MTC experts was related to *process* factors. In three of the five factors related to the manufacturing process, a very significant correlation between the factors and the automation probability has been extracted. The three identified depending factors for a high automation probability are the *existence of the process in manufacturing*, *stand-alone or combination of manufacturing processes*, and *required flexibility*. In terms of the other identified factors, whereas the process type does not significantly correlate with the automation probability, a significant negative correlation between the complexity of the application and the standard deviation has been extracted. The correlation suggests that a low complexity of the specific application should be aimed at to decrease the uncertainty of automation.

The last group of factors is related to the *predicted performance*. Four different factors have been allocated to the group. The reported factors are consumable use, repetitiveness, throughput and quality. The consumable use does not seem to be the main concern of the predicted performance group. However, the absence of a controlled consumable usage might increase the uncertainty of the probabilistic outcome. The lack of repetitiveness also shows a high uncertainty of outcome in its absence. Simultaneously, repetitiveness correlates very significantly with the automation probability. The co-occurrence might signpost the importance of the factor repetitiveness. Throughput and quality do correlate with the automation likelihood too. The following section will investigate the effects of the conducted research on the actual case studies. Due to the number of factors present in the technical network, a table will be used to express the technical values.

c. Case Study Results

The following section tests the predictive validity based on the case studies presented in the methodology section (see section 3.2.1). The aim is to use case studies and assess whether the model behaviour is predictive. The model analysis starts with the welding case study. For the following result presentation, not every individual critical success factor will be mentioned in detail, but critical success factors that characterise the specific function will be highlighted. The reduction of text is a response to the complexity of the technical network.

Welding

Table 6-14 presents the selection of states for each identified welding function. The conceptual framework has introduced the idea to functionally abstract the human task. Abstracting the welding case study has produced four different functions. Every process function contains different critical success factors. The first identified process function is welding. Welding as a manufacturing type is considered difficult due to the number of welding parameters to be controlled (current, potential, distance, etc.). The number of parameters additionally drive the process complexity. The functional entity contains multiple attributes and, therefore, the process function is a combined process. The function requires the flexibility to adapt to different situations in the welding process as different welding forms and directions must be addressed. Simultaneously concerns with the repetitiveness of the process arise. The individual setup creates novel situations for the operator/system. The previous process introduces variability as the position of the welding parts is not fully replicable. In the welding domain, the re-use of welding equipment throughout a production line is restricted. The application is a response to the material and the related reaction with environmental gases. Therefore, the design of a welding application can be very specific and will be a limiting factor for the reconfigurability of the production process. In terms of environmental factors, only temperature is considered critical for the welding application. Arguably, humidity is important depending on the specific welding process. In the presented case, the welding process is protected by an inert gas. The second process function describes the grinding of the welding tip. Occasionally, the welding tip must be ground to maximise the weld quality. The welding process describes standard welding from a technical perspective. The only concerning factor is the variability of the welding tip based on previous applications and should be considered when the grinding function is designed from a technical perspective.

Table 6-14: Critical Success Factor Selection for Technical Network – Welding

Process Function	*1 - Welding*	*2 - Grinding*	*3 - Pick and Place*	*4 - Tool Changer*
Critical Factor	***State***	***State***	***State***	***State***
Type	Difficult	Conventional	Conventional	Conventional
Complexity	Complex	Easy	Easy	Easy
Existing	Exists	Exists	Exists	Exists
Combined Process	Combined	Isolated	Isolated	Isolated
Flexibility	Required	Standard	Standard	Standard
Consumable Use	Yes	Yes	No	No
Repetitiveness	Nonrepetitive	Repetitive	Repetitive	Repetitive
Throughput	Aligned	Aligned	Aligned	Aligned
Quality	High	High	High	High
Variability	Present	Present	Absent	Absent
Variance	Absent	Absent	Absent	Absent
Dimension	Small	Small	Small	Small
Material	Normal	Normal	Normal	Normal
Input Cond	Normal	Normal	Normal	Normal
Output Cond	Normal	Normal	Normal	Normal
Handling	Easy	Easy	Easy	Easy
Interconnectivity	Interconnectable	Interconnectable	Interconnectable	Interconnectable
Interoperability	Interoperable	Interoperable	Interoperable	Interoperable
Tool	Complex	Intuitive	Intuitive	Intuitive
Reconfigurability	Restricted	Reconfigurable	Reconfigurable	Restricted
Control Complexity	Complex	Intuitive	Intuitive	Intuitive
Floorspace	Available	Available	Available	Available
Pollution	Absent	Present	Absent	Absent
Humidity	Absent	Absent	Absent	Absent
Temperature	Critical	Absent	Absent	Absent
Infrastructure	Present	Present	Present	Present
Structured	Structured	Structured	Structured	Structured

The pollution identified in the grinding function originates from the filler material that might pollute the welding tip. Function 3 and 4 are a pick and place, as well as a tool changing function. Those two functions are used to set up the workpiece and the equipment for the welding application. In terms of the special characteristics, the identified manufacturing functions are already well established. Pick and place as well as tool changing tasks have experienced high demand in the historical production environment.

Welding Results

Function	Process	Impact Automation	Automation Success	Performance	Factorial Impact Automation	Automation Success	Product	Factorial Impact Automation	Automation Success	System	Impact Automation	Automation Success	Environment	Factorial Impact Automation	Automation Success	OVERALL SCORE
	Process Type	65	60	Consumable Use	54	66	Variablity	54	64	Interconnectability	66	67	Floorspace	66	67	
	Complexity	64	0.340906	Repetitiveness	59	0.6362	Variance	76	0.93563	Interoperability	66	0.54073	Polution	66	0.666973	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	62		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	63					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
1							Handling	72								68
	Process Type	69	77	Consumable Use	54	91	Variablity	54	64	Interconnectability	66	66	Floorspace	66	66	
	Complexity	70	1	Repetitiveness	66	1	Variance	76	0.93563	Interoperability	66	0.66436	Polution	66	0.903762	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	72		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	71					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
2							Handling	72								98
	Process Type	69	77	Consumable Use	72	62	Variablity	76	67	Interconnectability	66	66	Floorspace	66	67	
	Complexity	70	1	Repetitiveness	66	0.65666	Variance	76	1	Interoperability	66	0.66436	Polution	66	0.695676	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	72		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	71					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
3							Handling	72								93
	Process Type	69	77	Consumable Use	72	62	Variablity	76	67	Interconnectability	66	66	Floorspace	66	67	
	Complexity	70	1	Repetitiveness	66	0.65666	Variance	76	1	Interoperability	66	0.60602	Polution	66	0.695676	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	72		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	71					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
4							Handling	72								93

Grinding Results

Function	Process	Impact Automation	Automation Success	Performance	Factorial Impact Automation	Automation Success	Product	Factorial Impact Automation	Automation Success	System	Impact Automation	Automation Success	Environment	Factorial Impact Automation	Automation Success	OVERALL SCORE
	Process Type	69	64	Consumable Use	54	91	Variablity	54	73	Interconnectability	66	66	Floorspace	66	66	
	Complexity	70	0.502242	Repetitiveness	66	1	Variance	57	0.72363	Interoperability	66	0.64611	Polution	66	0.903762	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	62		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	63					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
1							Handling	72								81
	Process Type	69	77	Consumable Use	72	62	Variablity	54	73	Interconnectability	66	66	Floorspace	66	66	
	Complexity	70	1	Repetitiveness	66	0.65666	Variance	57	0.72363	Interoperability	66	0.66436	Polution	66	0.903762	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	72		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	71					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
2							Handling	72								84
	Process Type	69	77	Consumable Use	72	62	Variablity	76	64	Interconnectability	66	66	Floorspace	66	67	
	Complexity	70	1	Repetitiveness	66	0.65666	Variance	57	0.94942	Interoperability	66	0.66436	Polution	66	0.695676	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	72		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	71					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
3							Handling	72								92
	Process Type	69	77	Consumable Use	72	62	Variablity	76	67	Interconnectability	66	66	Floorspace	66	67	
	Complexity	70	1	Repetitiveness	66	0.65666	Variance	76	1	Interoperability	66	0.60602	Polution	66	0.695676	
	Existing	72		Throughput	76		Dimension	79		Tool	66		Humidty	66		
	Combined Process	72		Quality	79		Material	74		Reconfigurability	66		Temperature	66		
	Flexibility	71					Input Condition	76		Control Complexity	66		Infrastructure	66		
							Output Condition	70					(Un-)Structured	66		
4							Handling	72								93

Figure 6-11: Technical Automation Probability for Welding, and Grinding Functions

The results are presented on the left-hand side of Figure 6-11. Three of the four functions show very promising results from a more technical perspective. Unfortunately, those three functions do not include the main attribute welding. The welding function does not achieve a higher overall score (68%). Reasons for that arise from three of the five categories. The categories are the process factors, performance factors, and product factors. The process factors with space for improvement are the process type, the process complexity, the combination of processes, and the required flexibility. The identified issues can inform later process design stages. Significant rework in the identified areas would improve the overall automation score. Similar findings apply to the performance factors, where the consumable use and the repetitiveness must be addressed. The main concern in the performance category is related to the repetitiveness of the function. A standardisation of the manufacturing process might lead to a reduction in the process and performance factors. From a product perspective, the process is exposed to variability in the process due to the changing position of the welding parts.

Grinding

The grinding process has been translated into four different process functions (see Table 6-15). The identified process functions are a grinding function combined with haptic feedback, the part inspection function for surface measurements, a pick and place function to manipulate the position of the parts, as well as a tool changing function. The grinding function is represented as a combined process. The combination replicates three different allocated attributes. As presented in the second part of the current chapter (section 6.2.2), the grinding function contains a grinding attribute, haptic feedback, and a small share of tool changing and setup attributes. The 'tool changing and setup' attribute reflects the operator preparing for the grinding operations. However, the grinding and haptic feedback function are a true combination of process attributes. During the grinding feedback, the abrasion is controlled by a measurement of the haptic feedback. Controlling the haptic feedback enables increased flexibility for different shapes and sizes of the product. In the grinding case study, the initial aim is to enable the grinding/polishing process of different products, and, therefore, flexibility is a requirement. The consumable use can be explained as the actual process in an abrasive process. The abrasive material of the tool must be replaced over a period.

Table 6-15: Critical Success Factor Selection for Technical Network – Grinding

Process Function	*1 - Grinding with F&T*	*2 - Inspection*	*3 - Pick and Place*	*4 - Tool Changer*
Critical Factor	**State**	**State**	**State**	**State**
Type	Conventional	Conventional	Conventional	Conventional
Complexity	Easy	Easy	Easy	Easy
Existing	Exists	Exists	Exists	Exists
Combined Process	Combined	Isolated	Isolated	Isolated
Flexibility	Required	Standard	Standard	Standard
Consumable Use	Yes	No	No	No
Repetitiveness	Repetitive	Repetitive	Repetitive	Repetitive
Throughput	Aligned	Aligned	Aligned	Aligned
Quality	High	High	High	High
Variability	Present	Present	Absent	Absent
Variance	Present	Present	Present	Present
Dimension	Small	Small	Small	Small
Material	Normal	Normal	Normal	Normal
Input Cond	Normal	Normal	Normal	Normal
Output Cond	Normal	Normal	Normal	Normal
Handling	Easy	Easy	Easy	Easy
Interconnectivity	Interconnectable	Interconnectable	Interconnectable	Interconnectable
Interoperability	Interoperable	Interoperable	Interoperable	Interoperable
Tool	Intuitive	Intuitive	Intuitive	Intuitive
Reconfigurability	Restricted	Reconfigurable	Reconfigurable	Restricted
Control Complexity	Complex	Intuitive	Intuitive	Intuitive
Floorspace	Available	Available	Available	Available
Pollution	Present	Present	Absent	Absent
Humidity	Absent	Absent	Absent	Absent
Temperature	Absent	Absent	Absent	Absent
Infrastructure	Present	Present	Present	Present
Structured	Structured	Structured	Structured	Structured

The second identified process function contains the inspection attribute. The inspection function includes operations for quality inspection and control of the part surface. The operation is not using abrasive material but experiences an effect of the abrasive material which leads to pollution of the part surface. The pollution might lead to a misinterpretation of measurement results. Sporadically polluted surfaces are not an issue for the human process inspection as they can be removed instantly by the operator. For the auto-inspection, the particles from the previous abrasive process must be removed before the inspection process. The related identified attribute is a 'visual inspection of the part texture'. The third function contains the pick and place attributes. The related attribute describes pick and place operations, which the operator must perform during the grinding process to manipulate the part position. The tool changing function enables a change between grinding and polishing tools.

The grinding results are rather promising for all the four identified process functions (see Figure 6-11). However, the first two functions, score slightly lower than the last two from a technical perspective. The first function is grinding with haptic feedback (81%). Reasons for a lower score can be derived from the process, performance, and product factors. The function demands flexibility and contains combined manufacturing attributes (grinding, haptic feedback, and setup) influencing the process factors. Additionally, the concerning performance factors are driven by the consumable use of the process. The product complexity is driven by an introduced variability by processes earlier in the production chain. Thereby, the initial defects are randomly located on the production surface. Similar effects arise from the product mix. The second function with a lower score is the visual inspection function (84%). The function is mostly affected by the product factors. Reasons for that are similar to the grinding function (variability and variance).

Beater Winding

The beater winding process is represented by three different automation functions (see Table 6-16). The identified process functions are sawing, a customised function, and the tool changing function. The first identified process function contains sewing attributes. Sewing is a conventional and well-known automation process with low complexity. However, after the winding process, the operator must cover the existing gaps between the thread winds with a needle. The clustering algorithm has allocated the operations within the sewing function. Therefore, visual feedback is required for process function 1, which increases the control complexity. The thread adds additional concerns to the product factor category through arising from the material factor. Function 1 has a limited capability to be reconfigured as the application of the sewing process is rather special for the beater. The second identified process function is the winding function. The attributes are translated into a customised function as the required winding process is not commonly used and, therefore, requires research input. Like the previous process function, product variability is introduced by using the thread. The novelty and variability of the process function lead to an increase in the control complexity. The third and last function is a tool changing function. The tool changing function is attributed as a novel function due to the second process function. In all the other categories, process function 2 behaves like previously identified tool changing mechanisms.

Table 6-16: Critical Success Factor Selection for Technical Network – Beater Winding

Process Function	*1 - Sewing*	*2 - Customised*	*3 - Tool Changer*
Critical Factor	**State**	**State**	**State**
Type	Conventional	Conventional	Conventional
Complexity	Easy	Easy	Easy
Existing	Existing	Novel	Novel
Combined Process	Combined	Combined	Isolated
Flexibility	Standard	Required	Standard
Consumable Use	Yes	Yes	No
Repetitiveness	Repetitive	Repetitive	Repetitive
Throughput	Aligned	Aligned	Aligned
Quality	High	High	High
Variability	Present	Present	Absent
Variance	Absent	Absent	Absent
Dimension	Small	Small	Small
Material	Difficult	Difficult	Normal
Input Cond	Normal	Normal	Normal
Output Cond	Normal	Normal	Normal
Handling	Easy	Easy	Easy
Interconnectivity	Interconnectable	Interconnectable	Interconnectable
Interoperability	Interoperable	Interoperable	Interoperable
Tool	Intuitive	Intuitive	Intuitive
Reconfigurability	Restricted	Restricted	Restricted
Control Complexity	Complex	Complex	Intuitive
Floorspace	Available	Available	Available
Pollution	Absent	Absent	Absent
Humidity	Absent	Absent	Absent
Temperature	Absent	Absent	Absent
Infrastructure	Present	Present	Present
Structured	Structured	Structured	Structured

The identified decision factors are used to calculate the results via the decision-support tool. As can be seen in Figure 6-12, the overall score of the beater winding tool looks promising for two of the three identified process functions (90% - sewing, 76% - Customised/Winding, and 91% Tool Changing Process). The biggest influences in the key areas process, performance and product for process function 1 can be derived from the combined attributes of sewing and the visual inspection, as well as from a variability and material perspective. For the customised function, the main factors are critically represented in the process category. A novel process combining winding and haptic feedback, as well as the required flexibility, drive the challenges related to the second process function. The product factors of the particular function are identical to the factors of process function 1 related to variability and the material. A combination of those challenges results in an overall score of 76%. The latter process function is the tool changing process. Due to the novelty of process function 2, a novel situation is created for the tool changer. Credit for the novelty is given by a minor challenge arising from the process category.

Threaded Fastener Assembly

Abstracting the threaded fastener assembly task by attributing the operations results in three dissimilar process functions (see Table 6-17). The three identified functions are auto-fastening, pick and place, as well as a tool changing function. The first process function includes attributes of 'pressing in and on', the 'visual perception of distance', and the 'visual perception of an object shape'. Even though the process type fastening can be considered a conventional production process, the additionally allocated attributes drive the functional complexity and incorporate different mechanisms. The investigated problem a fully flexible system that recognises a screw in an unstructured workspace and identifies the related drilling hole in the search space. The idea translates into flexibility demands for the fastening process and considers a product variance. The integration of different mechanisms allocated in process function 1 drive the control complexity. The second process function contains 'pick and place' attributes as well as attributes for visual perception of distance and object shape. The combination of factor translates into an identical list of critical success factors with the only exception of the consumable use. The last identified function is a tool changing function just alike previously described tool changing mechanisms.

Based on the decision factors, the overall score can be obtained. As can be seen in Figure 6-12, three different results can be obtained. The first result is related to the fastening process function (81%). Major influences for the performance of the process functions are caused by a combination of different mechanisms within the processes and a challenging product category. More specifically, the threaded fastener assembly process is complex, combines multiple mechanisms, and demands process flexibility. The performances factors for the first process function are influenced by consumable use. The product factors additionally challenge the automation process as the product displays variability (screws unstructured in search space) and variations of screw sizes.

Table 6-17: Critical Success Factor Selection for Technical Network – Threaded Fastener Assembly

Process Function	*Auto-Fastening*	*Pick and Place*	*Tool Changer*
Critical Factor	**State**	**State**	**State**
Type	Conventional	Conventional	Conventional
Complexity	Complex	Complex	Easy
Existing	Exists	Exists	Exists
Combined Process	Combined	Combined	Isolated
Flexibility	Required	Required	Standard
Consumable Use	Yes	No	No
Repetitiveness	Repetitive	Repetitive	Repetitive
Throughput	Aligned	Aligned	Aligned
Quality	High	High	High
Variability	Absent	Present	Absent
Variance	Present	Present	Absent
Dimension	Small	Small	Small
Material	Normal	Normal	Normal
Input Cond	Normal	Normal	Normal
Output Cond	Normal	Normal	Normal
Handling	Easy	Easy	Easy
Interconnectivity	Interconnectable	Interconnectable	Interconnectable
Interoperability	Interoperable	Interoperable	Interoperable
Tool	Intuitive	Intuitive	Intuitive
Reconfigurability	Reconfigurable	Reconfigurable	Restricted
Control Complexity	Complex	Complex	Intuitive
Floorspace	Available	Available	Available
Pollution	Absent	Absent	Absent
Humidity	Absent	Absent	Absent
Temperature	Absent	Absent	Absent
Infrastructure	Present	Present	Present
Structured	Unstructured	Unstructured	Structured

The second process function is similar to the first process function but does not improve the consumable use through automation. Hence, the overall score experiences an additional drop of 7% (to 74%). The third process function displays almost perfect technical characteristics for automation, even though no consumable use is anticipated for the tool changing mechanism.

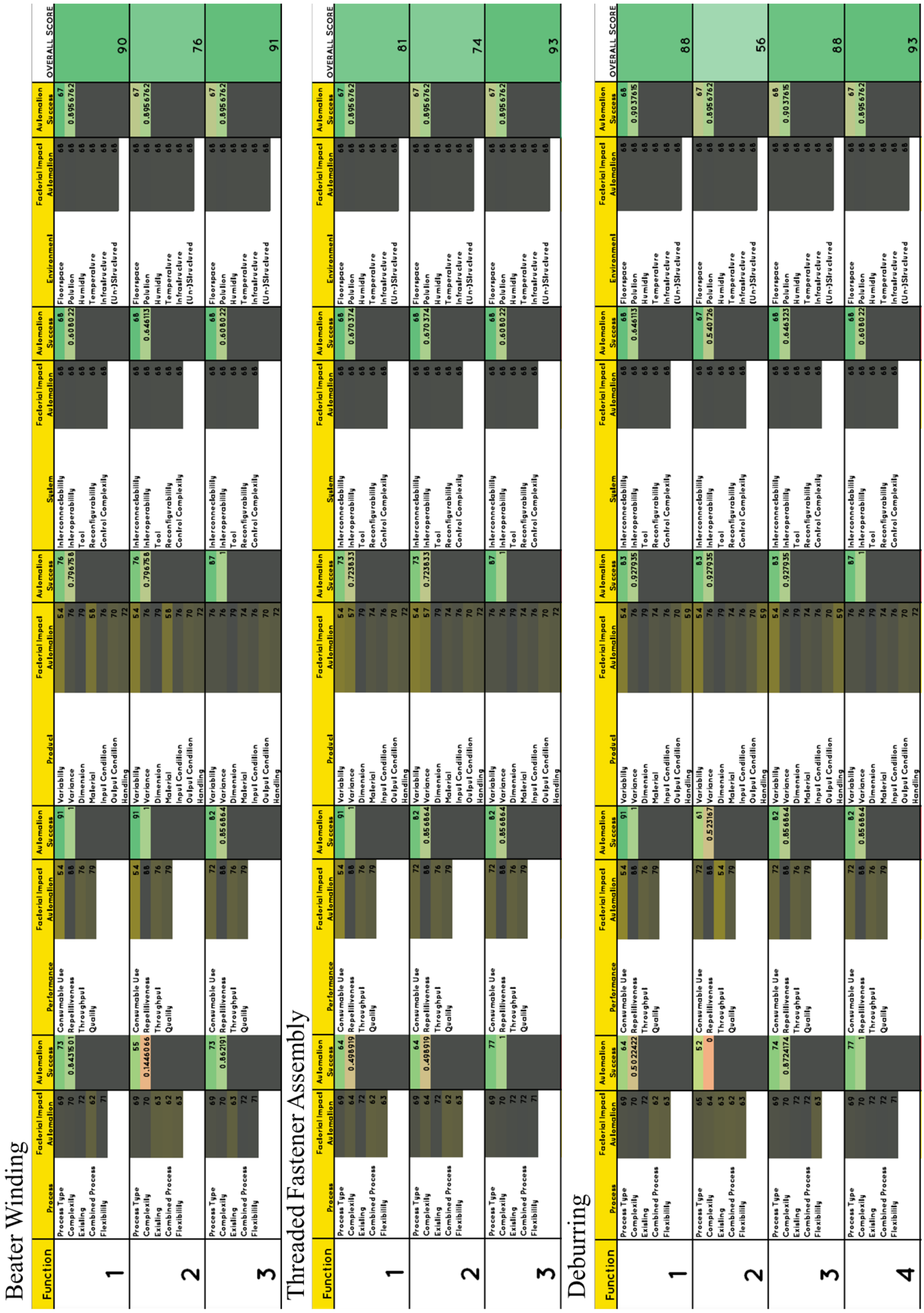


Figure 6-12: Technical Automation Probability for Beater Winding, Threaded Fastener Assembly, and Deburring Functions

Deburring

The clustering algorithm has identified four process functions contributing to the overall deburring process. The four derived functions are grinding with haptic feedback, inspection (visual-haptic feedback), visual inspection, and a tool changer (see Table 6-18).

Table 6-18: Critical Success Factor Selection for Technical Network – Threaded Fastener Assembly

Process Function	*Grinding with haptic feedback*	*Inspection*	*Visual Inspection*	*Tool Changer*
Decision Factor	**State**	**State**	**State**	**State**
Type	Conventional	Difficult	Conventional	Conventional
Complexity	Easy	Complex	Easy	Easy
Existing	Exists	Novel	Exists	Exists
Combined Process	Combined	Combined	Isolated	Isolated
Flexibility	Required	Required	Required	Standard
Consumable Use	Yes	No	No	No
Repetitiveness	Repetitive	Repetitive	Repetitive	Repetitive
Throughput	Aligned	Conflicting	Aligned	Aligned
Quality	High	High	High	High
Variability	Present	Present	Present	Absent
Variance	Absent	Absent	Absent	Absent
Dimension	Small	Small	Small	Small
Material	Normal	Normal	Normal	Normal
Input Cond	Normal	Normal	Normal	Normal
Output Cond	Normal	Normal	Normal	Normal
Handling	Difficult	Difficult	Difficult	Easy
Interconnectivity	Interconnectable	Interconnectable	Interconnectable	Interconnectable
Interoperability	Interoperable	Interoperable	Interoperable	Interoperable
Tool	Intuitive	Complex	Complex	Intuitive
Reconfigurability	Restricted	Restricted	Reconfigurable	Restricted
Control Complexity	Complex	Complex	Intuitive	Intuitive
Floorspace	Available	Available	Available	Available
Pollution	Present	Absent	Present	Absent
Humidity	Absent	Absent	Absent	Absent
Temperature	Absent	Absent	Absent	Absent
Infrastructure	Present	Present	Present	Present
Structured	Structured	Structured	Structured	Structured

The grinding task is an abrasive process implicating that direct contact between part and tool takes place. As a result, the grinding process must be equipped with a perception mechanism that prevents the tool from scratching the part surface during the deburring process. The grinding function of the deburring process is extended by visual perception attributes to identify the part shape, the texture, and the distance. The combination of multiple attributes increases the control complexity. Simultaneously, the function must allow the flexibility to react to burrs at different locations of the part driven by the product variability. Since deburring of holes in parts is rather specific in the equipment cannot be easily reconfigured to fit different manufacturing purposes. The second extracted process function is a complex inspection function. The inspection function is used to identify burrs within holes using a combination of tactile, and visual feedback for texture and shape. A combination of visual and haptic feedback requires research input and increases the complexity of the process by combining different perception mechanisms. The manual process using the hands is very fast. The specific combination of tools makes the second process function hardly reconfigurable to fit different purposes. The third function is a global visual inspection to identify parts on the surface. Similar to the previous processes, variability is presently caused by previous production processes. Due to the size of the part, handling the part is considered difficult. The deburring process further pollutes the part for visual inspection. The tool changing mechanisms is similar to the already presented tool changers in previous paragraphs.

The results of the technical network are divided into four different process functions. The four process functions are grinding with tactile feedback (88%), visual-tactile inspection (56%), visual inspection (88%), and tool changing (93%). For the grinding with tactile feedback process, the score is influenced by the combined process and required flexibility. The performance is influenced by the consumable use. From a product perspective, the main concern is the introduced part variability caused by previous processes as well as handling difficulties due to the weight of the part. The visual-tactile feedback shows the lowest automation feasibility over all investigated processes. There are multiple reasons for that. The first set of reasons arise from the process. The process type is difficult, complex, and novel. In addition to that, the automation requires a combination of visual and haptic feedback to analyse the part surface insight a drilling as well as demands process flexibility. The main concern from the process factor perspective is related to the throughput or speed of the process. An operator can perform the operation very fast but might require more time to capture, synchronise, and calculate the results from a technical perspective. The product factors are identical to the previous process function. The third process function is the visual inspection of the process. The process factors are negatively influenced by flexibility demand. However, no additional concerns arise from a performance perspective. The product is still influencing concerns related to variability and handling for the visual inspection process. Again, the tool changing factors for process function 4 are identical to previous case studies.

d. Predictive Validity Compared to Other Algorithms

To emphasise on the predictive validity of the presented model, the tool results have been compared to commercially available algorithms. Therefore, the mathematical model of the underlying mathematical network is compared with other commercial networks to validate the created results. Purposefully, the BNN from the Experts was recreated in a commercial toolbox (GeNIe 2.1 Academic) for assessment of the predictive validity of the MCMC method. A careful selection of different algorithms has been made. From the commercial tool, the EPIS algorithm (considered among the best algorithms to date) [330], the AIS [331], Likelihood [332] and the so-called "clustering" algorithm (clique-tree propagation algorithm) have been selected. The case study results were used for a Pearson correlation coefficient or bivariate correlation test as a measure of linear correlation between to variables, the covariance as a measure of independence between to samples and a confidence interval of similarity. The results are displayed in the following table (see Table 6-19).

Table 6-19: Algorithm Comparison.

Correlations, Covariance, and Confidence Interval of Correlation					
		EPIS	AIS	Likelihood	Clustering
Pearson Correlation		.936**	.949**	.918**	.957**
Sum of Squares and Cross-Products		1450.125	1389.129	1256.295	1431.728
Covariance		85.301	81.713	73.900	84.219
N		18	18	18	18
95% Confidence Interval	**Lower**	0.833	0.869	0.801	0.879
	Upper	0.977	0.979	0.976	0.990

As displayed, the algorithm correlates well with the present commercially available tools. In the table above, a correlation significant at the 0.01 level (2-tailed) with all the alternatives is depicted. Similarly, the covariance is significantly higher than 0. A covariance of 0 would be an indication of an entirely statistically independent sample. In the presented case, however, the combination of a strong Pearson correlation and the Covariance lead to confidence that the algorithm and mathematical model present similar results compared to a selection of other algorithms currently available. The presentation of the algorithm results and the connected comparison with other algorithms demonstrates the conceptual applicability so far.

6.3.3 Decision-Making for Automation Summary

A reflection on the network models presents a technical approache taken by the contributing expert group. From the technical perspective, the automation feasibility was approached by an in-depth technical understanding which arises from the nature of the institution. The different approache will influence the discussion section in the subsequent chapter. Before the discussion chapter, the following subsection will summarise the overall chapter.

6.4 Chapter Summary

The presented chapter has created the results based on five real case scenarios. Within the chapter, the focus was on displaying the results of the established decision support framework. The results are related to the process representation and modelling domain, as well as to the decision-making for intelligent automation domain. The following chapter will use the results and reflect on the initial research questions and the requirements arising from the environment for the conceptual framework. A comparison between the objectives and goals of the thesis with the results will be the basis of framework discussions.

7 Discussion

“The aim of discussion should not be victory, but progress.” – Joseph Joubert.

In the previous chapters, a conceptual framework has been created based on the initial findings of research stage 0. The identified problem was the *early-stage decision support for implementing intelligent automation in manufacturing businesses*.

The introduction section 1.1 has implicated that many manufacturing businesses criticise standard automation mainly for the lack of flexibility amongst various reasons [10]. The current situation may be described as the following: In the near future standard automation tasks might be automated to the extent possible and complex human tasks may remain. Simultaneously, the latest research indicated that an increase in task complexity necessitates more autonomous systems, especially in combination with the skilled labour shortage [70]. In other words, the increase in task complexity leads to systems that use more sensors and intelligence to cope with the challenges introduced by a more complex human task. Intelligent automation was pointed out by current studies as a possible response to those challenges [11]. It should be reflected on whether those findings implicate a paradigm change for the future. Previously, standard automation has been assessable via costing models in combination with historical data and predictable system design. In chapter 4, however, a study involving smart technology experts suggested that novel systems are difficult to be assessed via cost models. The experts pleaded for use of more pragmatic ways to assess the implementation of smart technologies. One reason for that was problems with return on investment (ROI) calculations. A possible cause is a lack of design information at an early decision-stage in combination with the unpredictability of a more customised (therefore novel) smart technology solution.

As a consequence, a novel, more pragmatic way to support the early-stage decision for implementing intelligent automation was found to be missing. This is confirmed by industry collaborators. Similar findings have been pointed out in other publications (see for example [228]). Related publications were either considering costing information, historical data, design information, or started with the assessment of intelligent automation systems at later decision stages (for example technology selection). Hence, a decision framework has been developed, which shall be discussed more carefully in the following sections. Two main uncertainties had to be modelled. The first uncertainty arises from a lack of system design information from an early-stage perspective within the process representation and modelling domain. The second uncertainty is related to the decision-making process caused by a lack of historical information related to intelligent automation and the sensitivity of business information. Before the process representation and modelling domain is discussed, the modelling had to be informed by the task analysis and human factor domain.

7.1 Task Analysis and Human Factor Domain

A reflection on the task analysis and human factor domain can be made with respect to several different aspects. The literature review shows that human task models are applied in several different ways. Not all the existing models follow the purpose of analysing the task for automation. Some of the models, like the PIAAC model, measure the competency of adults and matches the results with skills needed for a specific job [45]. Represented by increasing publications, the human task analysis for automation is steadily growing. Over time models have been developed that extended the physical task by adding cognitive elements [38] and other methods to extract the human skill for automation [49]. Regardless of the contributions, one of the problems that remain until today is a practical problem.

However, task analysis is not just a possible starting point. The contribution from the manual task analysis perspective was made due to the application of different manual task levels for the task analysis. The aim was to determine, which was the right level for the task attribution. As a result, different task levels starting from the lowest with SGT on an action level have been applied. During the conducted research, the observation was made that current task analysis methods, despite the contributions made to the understanding of the human task, require much effort to gain comprehensive automation information. For the application of the following decision model, the decision was made to analyse tasks on an operational level. The level was found to deliver appropriate detail, given the decision goal and limited resource and time constraint for a business case evaluation.

More research would be needed to confirm task analysis on an operational level as a generically valid result to decrease depth due to an increasing data quality/ decreasing uncertainty.

And yet, a more in-depth model could automatically assess the tasks for automation. However, several pieces are missing to conduct a task analysis using such sophisticated methods that reduce the analyst's effort (for example machine learning and image processing algorithms). In the future, decision mechanisms need to be presented on how to break-up continuous task data into discrete data (for example a video sequence automatically translated into a task structure). Therefore, knowledge must be gained towards attributes determining an operation's start and end, and how the relationship between tool, object, perception, physical task and decision-making can be represented. Such a determination requires additional knowledge about psychophysiological aspects to understand the relation between the physical and cognitive world of an operator and the environment. Examples are the relation between physical task and cognitive task, the relation between perception and cognitive task, the relation between physical task and perception, and the task dependencies (Design Structure Matrix [333]). The understanding of the task analysis and human factor domain led to the process modelling and representation part of the thesis. If an automation decision is made for greenfield planning, the starting point for the analysis comes at the end of the process representation model and the automation functions can be filled in manually.

7.2 Process Representation and Modelling Domain

Initially, the framework should establish a ground for the decision-making process by building up relevant process information based on limited initial information. In most of the research to date, solutions reflected a more technical perspective (see Table 6-10). The technical perspective should also moderate the financial risks of implementing smart technologies through reuse of manufacturing equipment (see Table 4-4). The additional identification of a re-use scenario from a process representation would be beneficial. The initial process information is mostly based on human task information.

Though, a generic method systematically transferring human tasks into a functional representation was previously missing. Core requirements for such a method were: Systematic and fast, easy to use, reduction of analysts influences, sufficient information provided for early-stage decision-making, and differentiation of tasks with regards to the level of Automation (LoA). The literature itself suggests two major limitations associated with current approaches. First of all, approaches related to manual task analysis processes have been criticised throughout the current literature as unreliable [334] and highly influenced by the level of expertise of the analyst [40]. Secondly, the way a task is fulfilled by a human operator might differ from the way that the automation system performs the task. Consequently, a comparison and mapping must take place on a functional level. Because of the different level of granularity that the HTA tool provides data related to human tasks (actions) to IDEF0 and the IDEF0, a common tool used to represent a functional model of a process, are however subjective to the viewpoints of the observer. To overcome the discussed issues, a clustering-based mechanism has been developed to translate HTA into the functional model. Reasons for that are:

- The clustering works on a different level than the HTA or IDEF0 analysis,
- follows a different objective (analyse individual operation attributes),
- is independent of the chronological structure,
- does not consider sequential dependencies unless indicated,
- and, thus, is not influenced through a task hierarchy by the executing analyst.

What can be seen from the beginning in Table 5-6, for example, is: The HTA structure presented is different from the allocated centroid. Even though ‘Select filler rod’ and ‘Grind tip of the electrode’ have been allocated by the expert in the same hierarchical level 1, the clustering algorithm has identified a different function behind this specific operation. And thus, significant differences between HTA/IDEF0 and the novel clustering application exist. The effect will be a functional abstraction independent from the hierarchical structure and based on limited attributes that can be selected by the tool user. The task analysis is effectively less influenceable by the expert. In this way, the algorithm could allow functions to be represented in different hierarchical parts but still be allocated in one functional block. Functional coverage could be assumed as generic within the task hierarchy.

Another aspect with regards to the bigger picture is the abstraction of human operations for automation requirement engineering. The proposed method delivers comparative results over all the case studies. The investigation to cluster the optimal function for requirement engineering demonstrates: *For some of the case studies* the *prediction* of the overall system functions *outperforms the experts' initial predictions about the system design*. The results also prove that, in general, functional attributes are the most critical information to cluster operations and to establish an automation system design. The results are comparable with the earlier findings from Everitt et al. [335] highlighting the functional approach of Bullock [336] related to a robotic manipulator as very practical. More detail, in contrast to that (see for example SGT), increases the chance of human deviation and, therefore, decreases the repeatability and quality of task analysis.

Based on the functional task abstraction, the clustering approach would enable the identification of a set of requirements transferrable to a set of skills from a technical perspective. As key attributes have already been identified (for example "cutting with a geometrically undefined cutting edge"), they could be linked to a specific automation requirement (process has to be capable of performing an abrasive production process, for example grinding). A connection between the functional abstraction and requirement engineering seems possible and fulfils the requirement (for example as indicated in [337] and for reuse in [338]).

The clustering algorithm including the developed classification was programmed as part of the toolbox and enables a simple binary attribution process to allow the transfer of key information. The importance of the attribution part is the systematic reduction of system design uncertainty via process functions that establish the ground for the decision-making process. The manual task has been translated into a functional description. A functional representation allows the consideration of only specific functions for automation. Therefore, different levels of automation can be achieved by automating only specific functions rather than the whole manual process. Due to the time limitations, only the k-means algorithm to manage the functional task abstraction has been presented. There is a possibility that other algorithms may perform faster than the k-means clustering algorithm. Observed performance issues were related to the length of the task analysis, when longer task lists led to a slight increase in a calculation time of the clustering algorithm (varying between 7 and 12 minutes). Consequently, future research is needed to consider different pattern extraction algorithms and classifications to increase the quality of the functional abstraction by comparison of algorithms and classification attributes. The performance of the clustering algorithm is also heavily affected by user performance. Even though the classification does not leave room for interpretation, the user needs knowledge about the underlying data attribution process. Otherwise, the k-mean algorithm may produce results that do not represent the underlying process functions. If the user selects the right attributes, there might be an opportunity to support later stages of the automation decision process. The attributes could be represented through a skill set, which may lead to requirement engineering approaches. The second uncertainty, which had to be modelled is related to the lack of historical data for the decision-making process.

7.3 Decision-Making Based on Limited Information

The starting point for automation decision-making is the model presented in Figure 2-2. The figure describes the decision cycle of industrial innovation. Firstly, based on the company strategy and investment plans, an early-stage decision is made about a specific process. Based on the decision, the product and process can be designed for automation. The design of product and process allows the selection of specific manufacturing technology. The review of the decision-making literature reveals trends within the specific categories.

First of all, the fast-paced development of technology development in the area of automation with regards to smart technologies has created a gap between the contributions of previous strategic research and reality. Different strategic papers accumulate factors important for assessing and implementing automation but haven't been connected to the smart technology area yet. The solution was an update of the standard automation perspective using smart technology experts towards intelligent automation (chapter 4). The generated knowledge was used to inform the decision-making process. Product and process design for automation as well as technology selection is considered later in the decision process and relies on information that is not available at an early stage. Previous early-stage decision-making tools have developed costing models based on highly uncertain data (for example design assumptions [20], [197]) or developed to prepare the process and product design for automation stage [195]. Other early-stage decision-making approaches have chosen risk-based approaches, which inspired the investigation. Regardless of the individual contribution to the knowledge of each individual publication, a reason has been identified to neglect following any of the presented approaches (strategic level rather than technical level, relying on historical data, neglecting missing design knowledge for TRL assessment of customised products, etc.).

The identified approach that was remaining related to a probabilistic assessment using expert knowledge. Several reasons have been contributing to the decision. The reasons were a lack of historical data forbids using a database-driven approach, the high complexity and interrelations do not allow the application of logic approaches, causal reasoning was presented to be a key factor for trust and result quality, and the probabilistic approaches allow updating in the future. Simultaneously, missing casualisation among the established knowledge base (critical decision factors, as well as a lack of historical data) led to an expert elicitation approach as the remaining option. However, the established critical success factor data was used later to assess the elicited expert knowledge.

7.3.1 Extracting Critical Success Factors

A clear limitation of the expert elicitation was the number of experts available for the investigation. Only two different partners have contributed with 19 experts in total, which prevented the development of a more generalised network. The results should be treated carefully, as a possible bias cannot be excluded in such a sample size. The DELPHI-method was used to elicit the expert knowledge and has proven itself useful for the establishment of the causal relationships. Evaluating the validity of the networks, one main character was identified. A technical network has been created by the manufacturing technology experts. An investigation of the expert responses allowed the validation of the given expert responses in comparison to the other experts. Reflecting on the collection of factors, two kinds of critical factors have been collected by the experts that contribute differently to the modelling problem. Some of the factors are necessary for the problems and build the foundation (for example no pollution in the technical model presented in section 6.3.2). However, they are important for manufacturing regardless of whether the process is automated or not.

From a technical perspective, the results from the expert input are found to represent the results from different technical perspectives. First, the experts have identified multiple factors from the task complexity environment, but also pointed out factors related to the smart technology studies and more common technical decision factors. It can be summarised that the technical model shows partially strong similarities with different technical aspects of automation. The technical perspective can be applied regardless of the underlying business network.

7.3.2 Decision-Modelling (Uncertainty Mitigation via Bayesian Belief Network)

As previously mentioned, one network has been created and used for the modelling process. The network model was created using an importance sampling algorithm (an artificial intelligence model frequently applied to mitigate problems related to high probabilistic uncertainties based on expert knowledge). The evaluation of the sampling method with a comparison to commercially available algorithms (using GeNIe2.0) has suggested solid results from a mathematical perspective. All displayed correlations with commercial assessment tools exceeded a value of 0.918 for the network prediction. After the importance sampling algorithm, a causal relationship between the factors and the individual impact of each factor in combination with other factors could be assessed.

The results are exhibited in Figure 7-1. For the first time, the results have presented a numerical, probabilistic, and causal relationship between technical factors as well as the parent nodes. Causal relationships are important as associations inform improvement on the current technical conditions for intelligent automation (for example in combination with what is presented in [144], [146] to inform the design stage). Previously, the strategic papers were qualitative and high-level [18], and conceptually discussed the implementation of automation acknowledging critical factors (see for example: [127], [128], [132]). From an early-stage decision support aspect at stage gate 2, the system design had to be known or assumptions have been made about the current uncertainties (see for example the known component design for TRL approach in [199]). Too often early-stage decision-making and later stages of the automation decision-process, like design stage and/or technology selection seem to be mixed up.

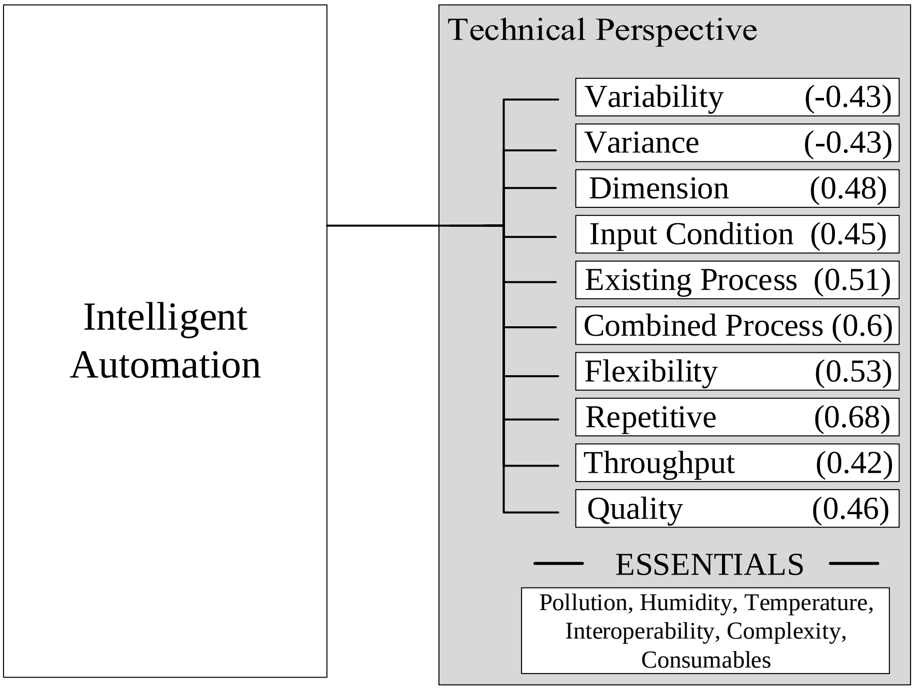


Figure 7-1: Strongest Success Factors with Significant Causal Influence on Intelligent Automation

Current work aims to determine the right processes for intelligent automation from a business perspective, and yet neglects the technical risk perspective at the beginning. The created network presents a technical perspective on the decision-making problem for implementing intelligent automation. Contemplating the technical network, the impression gained suggests that the technical network can be applied regardless of the nature of the business or company yet lacks presenting a business perspective. The disconnection between a technical and business- driven model is a problem. However, a disconnection is natural due to the discussed differences from business to business, which require the development of user-specific business networks.

The overall strategy suggestion for the technical network in combination with the business network may be described as the following four cases:

i. The technical network shows promising results => full automation of process function

ii. The technical network shows doubtful results => no automation of process function, eventually research activities

Without a business perspective, the technical network would produce wrong suggestions from a technical automation perspective. The phenomenon is presented throughout the decision-making domain (for example in MCDM approaches [194]). Therefore, the suggested solution is a combination of business and technical perspective.
The technical likelihood is created by a selection of the decision-factors for the technical network. The results may lead to different scenarios. In some cases, the decision-makers should see whether the process function should be automated together with another process function. Semi-automating a process may require human-robot interaction and drive the company towards full automation for safety reasons. In automation cases of bottleneck processes, increased productivity may lead to a re-distribution of workers in later processes due to a shorter takt time. The last scenario describes a scenario, where one process function and another process function have a positive automation score and process function in between is questionable for automation. However, considering automation for the whole process, the decision-makers may decide on a full-automation scenario. After the project has finished, the network must be evaluated to allow a backpropagation of the probabilities, as presented in [339].

The technical decision-support framework has been tested using real case studies by the industry. However, due to the sensitivity of the related process information and the legal agreement, the results couldn't be presented in the thesis. Nevertheless, feedback was requested from the industry and discussed next.

7.4 Industrial Impact

The research results and the decision support tool were discussed with the industrial partner Siemens to evaluate whether the tool contributes to the automation decision-making process. Questions have been raised to the lead engineers. The questions explore whether the researcher understands the related issues, the tool fully satisfies the business demands, and whether the lead engineers aim to use the tool within the company. Four lead engineers, who participated in the workshop, have replied to the distributed survey. The questions were designed in a way that the respondents could move a slider to the appropriate percentage. In Figure 7-2 and Figure 7-3, the range was designed from 'Not at all' to 'Totally agree'. For the first question, the respondents reply with 83% that the research fully understands the arising problem within the industry (see Figure 7-2).

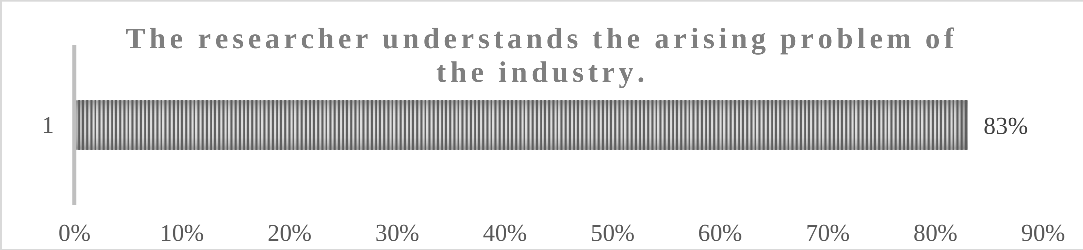


Figure 7-2: Q1: The research understands the arising problem of the industry.

The second question is related to the decision support tool. The aim is to understand whether the tool fully satisfies the business demands of the company. The engineers answer the question with 69%. Initially, the percentage seems to be quite low.

It is worth to be mentioned that so far only a first prototype of the decision-support tool has been created. The decision support tool lacks clear instructions and only demonstrates the functionality of the specific integrated algorithms. The tool has not only been tested on the presented case studies but also on industrial case studies, which are subject to a non-disclosure agreement. Even though the individual functions have been proven to work on real case scenarios, the decision support tool would require more effort to create a commercial solution. However, the support tool only covers the initial step of the automation-decision process and neglects to cost. From a business perspective, the risk probabilities can be used to design the automation system sustainably by tackling the identified issues and to build a technical risk model (Figure 7-3).

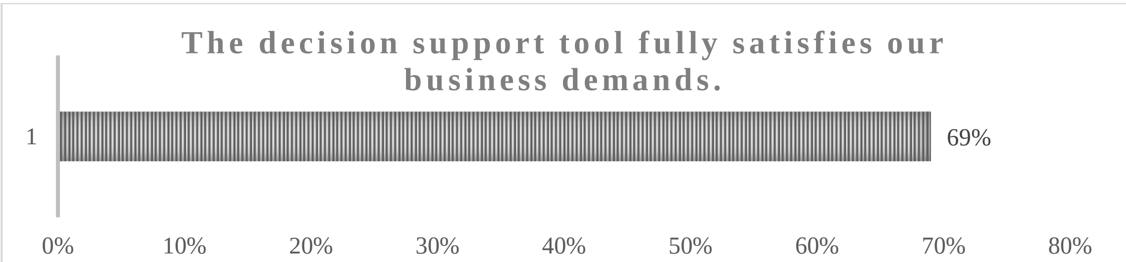


Figure 7-3: Q2: The decision support tool fully satisfies the business demands.

The last questions presented asks the lead engineers whether the company aims to use the created toolbox. 100% of the respondents aim to use the tool within the company. Even though the decision support tool does not seem to fully satisfy the business demands, the lead engineers aim to use the tool within the company (Figure 7-4). The responses might be an indication of the research gap that has been identified. Companies might see a value in a more sophisticated approach towards selecting the right processes for automation to prevent financial loses. Especially since mistakes at early stage decisions are more expensive than mistakes that occur at the end of an automation project.

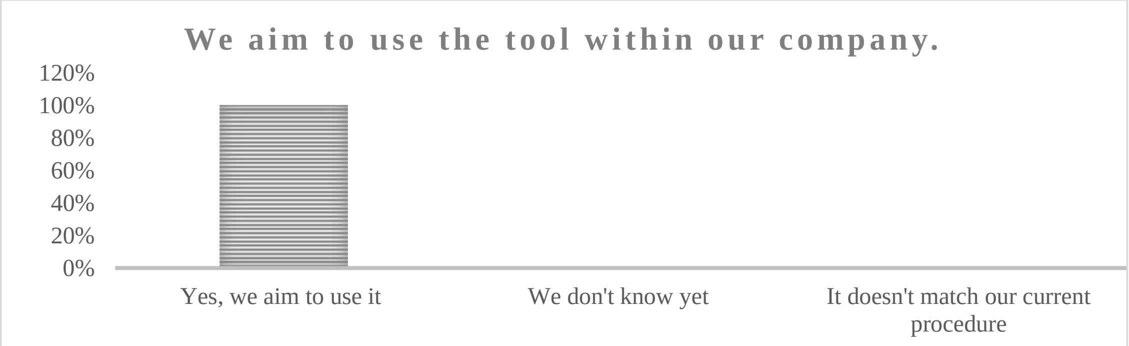


Figure 7-4: Q3: We aim to use the tool within our company.

Future work might be able to close the gap of the current status and to fully satisfy the business demand. The requirement engineering approach and a connection to the costing prediction domain might give valuable early-stage information to companies for a sustainable automation design.

7.5 Chapter Summary

This chapter has discussed several achievements in different research domains. The task analysis and human factor domain have investigated the appropriate level of detail for automation task analysis. The investigation found that an operational task level shows the ideal depth for further analysis. Based on the task-analysis finding, a connection between the initial human task and the process representation and modelling domain could be established through operation attribution. In the process representation and modelling domain, a clustering algorithm was used to extract critical process functions from the manual task in a semi-automated, repeatable manner using operation attribution. The attribution process leads to a reduced analyst influence on the abstracted task and prevents forgetting elements in the task list (such as tool changing from some of the experts). The application has demonstrated that the algorithm outperforms the expert predictions in some of the cases with regards to later system design. The reduction of the design uncertainty in the process modelling and representation domain led to the decision-making for automation process based on a determined design. First of all, the extraction of critical success factors via DELPHI-method as well as the establishment of prior probability networks enables a causal relationship among factors that were used to rate the individual process function. The causal relationship has been established using artificial intelligence to model the interrelationship model via Markov-Chain Monte-Carlo importance sampling. Based on this relationship, each identified process functions can be rated in terms of automation feasibility from a technical perspective, which was provided by MTC experts. The remaining limitations are related to confirmation of the different algorithms (k-means and MCMC) as well as a confirmation of the results related to the individual case studies. More experts may be needed to confirm the expert inputs from a technical perspective.

8 Conclusion

"Reasoning draws a conclusion but does not make the conclusion certain, unless the mind discovers it by the path of experience. – Roger Bacon

The tremendous development of manufacturing, especially with regards to smart technologies and systems under the new paradigm Industry 4.0, is believed to have a profound impact on manufacturing businesses. For a long time, standard automation strategies were followed by automating highly repetitive, monotonous, and homogenous jobs. Naturally, the remaining manual tasks are complex and difficult to automate. New automation solutions demand more flexibility and intelligence. The required flexibility can be provided using more adaptive and autonomous solutions. Intelligent automation is perceived as a possible solution to the arising requirements. However, this transition is still challenging due to the uncertainty in evaluating business benefits and technical risks associated with the implementation. Therefore, to support the appraisal of intelligent automation solutions, the presented thesis centres around the assessment of existing manufacturing processes for intelligent automation from an early-stage, business case evaluation perspective. A more pragmatic and technical approach to the current approach promises to reduce the risk of uncertainty and subjectivity implementing intelligent automation and should increase the confidence of decision-makers. The overall aim has been divided into five different sub-questions (see Chapter 1).

8.1 Research Questions Revisited

The five central questions arising from the initial aim have led to the development of a decision-support framework:

i. *Are there existing description models to represent the available information at an early- stage?*

The answer to that question is: Yes, there are existing description models, but the existing models have limitations when applied to the overall research problem. Hence, a new model had to be developed. Based on the literature review arising from research questions (i), the current knowledge with respect to

- the human factor and task analysis domain,
- the process representation and modelling domain,
- as well as automation-decision-making domain

had to be updated and investigated. Based on the established knowledge base, the thesis was later informed as part of the framing process.

ii. *What are the current trends that might affect early decision making for intelligent automation?*

Despite the contributions from many different domains and the output from different research groups, the decision-making process required by the current practitioners demands a new approach.

Several reasons have been held responsible for that:

- Shortage of historical data due to data sensitivity and novelty of systems,
- missing design information at an early stage, and
- costing identified as the most important decision-factor, yet
- reported difficult as novel (smart) systems cannot be sufficiently and reliably costed,

As the way automation systems can be characterised changes over time (from standard applications to more autonomous and flexible applications), the way of assessment seems to change and show similarities with other areas like construction or project assessment.

iii. *How can the early-stage information be systematically processed towards intelligent automation decision-making?*

The posed question was initially difficult to answer. The accumulated knowledge of the task analysis and human factor domain has not yet presented a systematic and functional way to represent and model the manual task for automation. Therefore,

- a novel method has been developed using clustering to abstract manufacturing attributes from an HTA analysis on operation level,
- to achieve a functional representation, which mitigated the effects of the previously mentioned design information uncertainty.

The resolution of the design uncertainty eased the decision-making process as important structural information was now available. The functional approach additionally connects to a requirement engineering approach, which can be used to influence future product and process design stages for intelligent automation.

iv. *How to assess the manufacturing process based on limited available information for intelligent automation implementation?*

The circumstances recognised as a result of the research question (ii) led to

- a novel probabilistic assessment approach based on expert elicitation
- from an early-stage perspective,
- which, for complexity reasons of the probabilistic network, required the use of an importance sampling algorithm.

The algorithm used in the presented approach was compared to other commercial importance sampling algorithms and found to deliver a sufficient mathematical performance based on the expert input.

v. *How to validate the results from the assessment?*

The conceptual model was used to develop a comprehensive and interrelated mathematical framework. The mathematical framework was used for the development of a decision support framework for the implementation of intelligent automation. The developed tool in combination with historic centre case studies enabled the validation of the decision support framework. The results show that the functional representation of the manual task establishes a basis for the decision-support. Initially, a technical perspective should be applied.

8.2 Contribution to Knowledge

Four areas of contributions to knowledge are considered to be made by the presented thesis:

a. The establishment of an early-stage decision-support tool for the implementation of intelligent automation based on limited information.

The first contribution to knowledge addresses an identified gap in the literature. The development of an early-stage decision-support tool for the implementation of automation has not been reported yet. Previous work relied on design information for the automation system to support the decision-maker via costing information or by use of historical information. The presented framework can be used at an early decision-stage (Gate 2) as presented in Figure 1-2, which represents the stage-gate diagram. Gate 2 describes the assessment of novel technologies in a preliminary manner.

b. *Extending knowledge from human task analysis to automation function via a novel clustering approach*

Part of the decision-making support tool was a systematic representation of human knowledge based on attributed manual operations. The attribution leads to a mitigation of system design uncertainty and enabled a functional representation. More specifically, the attribution of the manual operation led to the employment of a clustering algorithm to functionally abstract the production process. The previous discussion chapter has indicated the importance for the future of automation decision-making allowing the automatic connection between task analysis via cameras, sensors, and systems.

c. *Novel application of a Markov-Chain Monte-Carlo method in expert elicitation*

Based on the functional abstraction, a Bayesian Belief Network has been developed, which supports the assessment of each individual process function. The assessment of different process functions allows for different levels of automation. The BBN is developed using expert elicitation (DELPHI-method) to create a relationship model for the critical success factors. Due to the limited information and the complexity of the problem, an artificial sampling algorithm, the Markov-Chain Monte-Carlo method, was used to artificially establish a representation of dependency information within the Bayesian Belief Network. The co-occurrence analysis of the MCMC method led to a probabilistic score, which represented the likelihood of success for each individual function based on the critical success factors.

d. *Model of causal relationship among critical success factors from technical perspective*

Throughout the modelling process, the samples were recorded to evaluate a causal relationship between the critical success factors in combination with each other. Even though the individual influences were known, the MCMC method enables an assessment of a function based on a variation of interrelating factors. The modelling approach, therefore, established a clear causal relationship among the critical success factors for implementing intelligent automation.

Besides the contribution to knowledge, the research output has produced achievements on a smaller scale. Minor contributions to knowledge are

- the extension of task attributes to include visual and tactile skills,
- and the computation tool to facilitate the framework implementation.

The research was limited by factors that shall be mentioned in section 9.3, which eventually prevented the author from exceeding the results or limited author's choice to the presented research methodology.

8.3 Research Limitations

Four clear limitations to the research had to be recognised:

1. *Limited Number of Companies Providing Sensitive Business Data*

The manufacturing processes and related parameters are considered sensitive business parameters, which prevented many companies from transferring data. The aggregated knowledge leads to competitive advantage and possible prevents other business from entering a specific market. As a consequence, the first difficulty was related to a lack of sensitive business data, which was an initial limitation for using empirical methods to generate knowledge about critical success factor relationships.

2. *Limited Number of Companies Contributing to Expert Knowledge*

Due to a shortage of sensitive business data, the interrelation of critical success factors had to be established using expert knowledge. And yet, only a limited number of companies and experts contributed to the expert elicitation. The two main factors were the time limitation of the study, as well as the limited number of experts with the necessary background in the intelligent automation domain. Even though mathematical methods were used to limit the resulting uncertainty, more access to experts from different companies would have enabled the establishment of a more generic network.

3. *Limited Number of Case Studies to Prove the Concept Support Tool*

After the decision-support tool was created, a validation using historic centre case studies has been carried out. Even though a careful selection of historic centre case studies was made, access to more case studies would have helped to identify additional weaknesses within the attribution and/or decision-making process. It is worth to be mentioned, however, that the presented case studies are not the only case studies that have been assessed but a non-disclosure agreement with the partners does not allow the display of sensitive data.

4. *Limited Time to Commercialise Decision Support Tool*

The last limitations of the thesis are related to better commercialisation of the tool. As the industrial responses demonstrated, the tool must be further developed to fully satisfy the current business demands. Nevertheless, the value of an early-stage decision-support for the implementation of intelligent automation has been industrially recognised. The statement is not only based on the survey but also based on the oral feedback the research has received from the contributing experts. Even though such decisions are already being made without the tool, an application would increase the confidence for the higher management, even to benchmark individual projects against each other in a reliable manner.

8.4 Implications on Practise and Future Work

Especially related to the systematic representation of task knowledge, the question may be asked why the clustering algorithm to systematically represent task information is considered important in this research. The answer to that question requires a look into the future of automation decision-making. Until today, automation decision-making requires an expert that describes the manual task via task analysis tools such as, for example, the HTA. Such an analysis is time-consuming and highly affected by the individual analyst. The information is generally manually transferred into a process description model (like for example SADT/IDEF0). The margin for errors increases through the human factor. At the minute, two factors are key. Those two factors are the experience and knowledge of the task analyst, as well as the experience and knowledge of the automation engineer.

In the future, reliable automation decision-making may be done via task analysis through visual perception. The task could be recorded via the visual system and, by means of image processing algorithms, specific tasks, tools, and ergonomic positions can be identified. Additionally, the transition from one human operation to another could be identified using tool and body posture information, as well as information about the perception senses required for a specific task (gloves with force and torque sensor, eye-tracking camera, electroencephalogram (EEG) sensor and psychophysiological relationships. Hereby, the research must be conducted to increase knowledge about psychophysiological relationships. Psychophysiological relationships describe the relations between mental and physical processes.

The resulting continuous information stream of the recorded task would lead to a continuous description of the manual production process like an HTA analysis. Based on the allocated attributes describing physical, perception, and psychophysiological data, a pattern recognition algorithm (like clustering) could be used to functional decompose the human task. The task should be attributed and automatically transferred into process functions based on image processing and task information.

A process function allows both, a connection to requirement engineering and early-stage decision support. A combination of decision support and requirement engineering may then inform the future steps of implementing intelligent automation via process and product design for automation techniques as well as the technology selection process.

To extend the presented decision-making support, a connection between risk and costing might be interesting for the future. Based on the probabilistic findings presented within the thesis, a cost-risk model might be developed, which increases the confidence of high-level decision-makers on the presented calculations and results.

From a more general perspective on the presented framework, several points can be pointed out, which might be interesting for future research. First, due to the time limitations, an empirical investigation and comparison of different clustering algorithms and importance sampling algorithms must be done in the application area. The investigation results can be improved by approaching more companies for the confirmation of results and to generalise the models fusing into a generic decision network model.

Furthermore, with regards to the future of the research area, investigating the identification of human process functions automatically based on a combination of tactile, visual, and cognitive sensors is suggested. The arising model can be improved by a better understanding of psychophysiological relationships between the perception senses, the brain, and the body and inform the task complexity.

Finally, a database should enable the connection of the process functions with automation components taking a requirement engineering approach. In this way, mapping a recipe of a production process with a skill/requirement set of an automation system might be possible.

9 References

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10 Appendix

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APPENDIX A

Welding Case Study with Binary Attribute Matrix for Operations Level

Operation Name; Attributes →	*#*	*Joining through welding*	*Cutting with geometrically undefined cutting edges*	*Pick and Place*	*Tool Changing & Setup*	*Visual Inspection*	*Visual Perception Distance*
1.1 Select filler rod	1	0	0	0	1	0	0
1.2.1 Selectelectrode	2	0	0	0	1	0	0
1.2.2 Grind tip ofthe electrode	3	0	1	0	0	0	0
1.2.3 Select collet and ceramicnozzle	4	0	0	0	1	0	0
1.2.4 Assemble torch	5	0	0	0	1	0	0
1.3.1 Remove grinding leftovers	6	0	1	0	0	0	0
1.3.2.1 Place based on holderon bench	7	0	0	1	0	0	0
1.3.2.2 Attach gas supply	8	0	0	0	1	0	0
1.3.2.3 Secure welding piece	9	0	0	1	0	0	0
2.1 Place foot on foot pedal, and depress	10	1	0	0	0	0	0
2.2 Put on gloves	11	1	0	0	0	0	0
2.3 Hold torch in right hand using pen grip	12	1	0	0	0	0	0
2.4 Hold filler rod in left hand	13	1	0	0	0	0	0
2.5 Move torch and filler rod	14	1	0	0	0	0	0
2.6 Adjust equipment position	15	0	0	0	0	0	1
2.7 Remove objects impeding movement	16	0	0	1	0	0	0
3.1.1 Set and turn on power at the welding set	17	1	0	0	0	0	0
3.1.2 Turn on gas atthe gas cylinder	18	1	0	0	0	0	0
3.1.3 Put on welding mask (visor raised)	19	1	0	0	0	0	0
3.2.1 Position torch at tack location	20	1	0	0	0	0	1
3.2.2 Pull down visor	21	1	0	0	0	0	0
3.2.3 Pick up and position filler rod	22	1	0	0	0	0	0
3.2.4 Fully depress foot pedal	23	1	0	0	0	0	0
3.2.5 Dip filler rod in centre of the weld pool	24	1	0	0	0	0	0
3.2.6 Remove rod	25	1	0	0	0	0	0
3.2.7 Gradually release foot pedal	26	1	0	0	0	0	0
4.1 Position torch at weld start	27	1	0	0	0	0	1
4.2 Pick up and position filler rod	28	1	0	0	0	0	0
4.3 Fully depress foot pedal	29	1	0	0	0	0	0
4.4.1 Stroke filler rodin and out of weld pool	30	1	0	0	0	0	0
4.4.2 Feed filler rod through the fingers	31	1	0	0	1	0	0
4.5 Control torch movement	32	1	0	0	0	0	1
4.6 Modulate current	33	1	0	0	0	0	0
4.7 Control foot pedal	34	1	0	0	0	0	0
5.1 Taking off equipment	35	1	0	0	1	0	0
5.2 Turn off power and gas supply	36	0	0	0	1	0	0
5.3 Remove welding plates from test piece holder	37	0	0	1	0	0	0
5.4.1 Visually inspect top surface of weld	38	0	0	0	0	0	1
5.4.2 Visually inspect under surface of weld	39	0	0	0	0	0	1

APPENDIX B

Tungsten Inert Gas Welding

Tungsten Inert Gas (TIG) Welding is a joining process, usually manually applied in aerospace applications, fusing two parts along specific connection points or lines. The application is characterised by the production of higher quality welds in comparison to conventional welding processes.

Figure 10-1: TIG Welding Process

Reasons for not automating the processes are mostly related to a lack of information about the process with high dimensions of complexity as well as thermal part deformation difficulties. Commonly known, TIG welding is mostly used for different alloys in aerospace applications as the mechanism provides superior welding joints compared to other welding connections. The gas shields joints against reactive environmental gases (like oxygen) and prevents undesirable changes of material properties during the welding process. The need to automate the processes is driven by health and safety concerns related to the gas, heat and ergonomic concerns. A connection of the parts in the process is, hereby, fully established after cooling down the metal beyond the fusion temperature of the different material combinations. The metallic product in this case study consisted of three components, two halves and a pipe. The two halves are characterised by a geometrically complex shape. The halves are placed onto fixtures for positioning and joint by welding. The components respect the process requirements of a specific overhang width, geometrical shape of chambers and a constant gap between the two halves. The final product must be completely hermetically sealed by welding and a leaking test performed to check for air tightness.

Grinding

Grinding is used to create a smooth transition/flow among the surfaces on each component. The removed material of grinding must be kept minimal and the part form should not significantly differ from the original part geometry. For the specific parts, the surface flow is critical to the functionality. The component ground has many features, including a grade, a joint, and corresponding radii. Multiple different grinding wheels are changed according to features ground and reconditioned accordingly during the grinding process.

Figure 10-2: Grinding Process

The company executes two finishing processes, grinding and polishing. The difference between processes lies in the purpose of the finishing operation. Grinding aims to remove a thin layer of material from the surface by moving the part against a spinning wheel with an abrasive surface (<2750 rpm) to improve the dimensional surface precision of previous manufacturing operations. Polishing, in contrast to that, removes single particles from the surface to improve the surface profile. A smooth profile is produced by moving the part against a polishing wheel with a smaller grain-size of the abrasive material (<2750 rpm). The generic purpose of polishing is important for parts that are required to have specific tolerances in geometry and surface roughness/texture.

Beater Winding

The drum beater production of in the percussion music industry demands skilled operators. The operator manually winds an acrylic yarn around a pre-build beater core (see picture below). For the winding process, a tacit control mechanism to adapt tension forces during the beater winding process are required but cannot easily reproduced by an automation system. During the investigation of Zhao et al. an investigation into automating the beater production process has been initiated [340]

Figure 10-3: Drum Beater Winding Process

In the beater winding process four different beaters are produced, which are soft, medium, soft-hard and hard. The product variance leads to a process variability in the diameter of each finished beater. Additionally, beaters vary in the number of windings (between 120 and 140 times). The number of windings has an impact on the beaters wound diameter. Due to the nature of the process the final form deviates from an ideal circular shape, which increases the requirements for the stitching process. The beater is finished via 4/5 stitches at the top and bottom to attach the loose ends as well as two circumferential threads to prevent the wound threads from moving on impact during playing.

Deburring

The principle of de-burring is to remove any sharp edges from the components, applying light pressure to generate smooth transitions between surfaces on the component without modifying the component's features at all. In the case study, the component is CNC machined from a raw material block to create specific design features: holes, cavities, threads and surfaces with different inclinations and intersections.

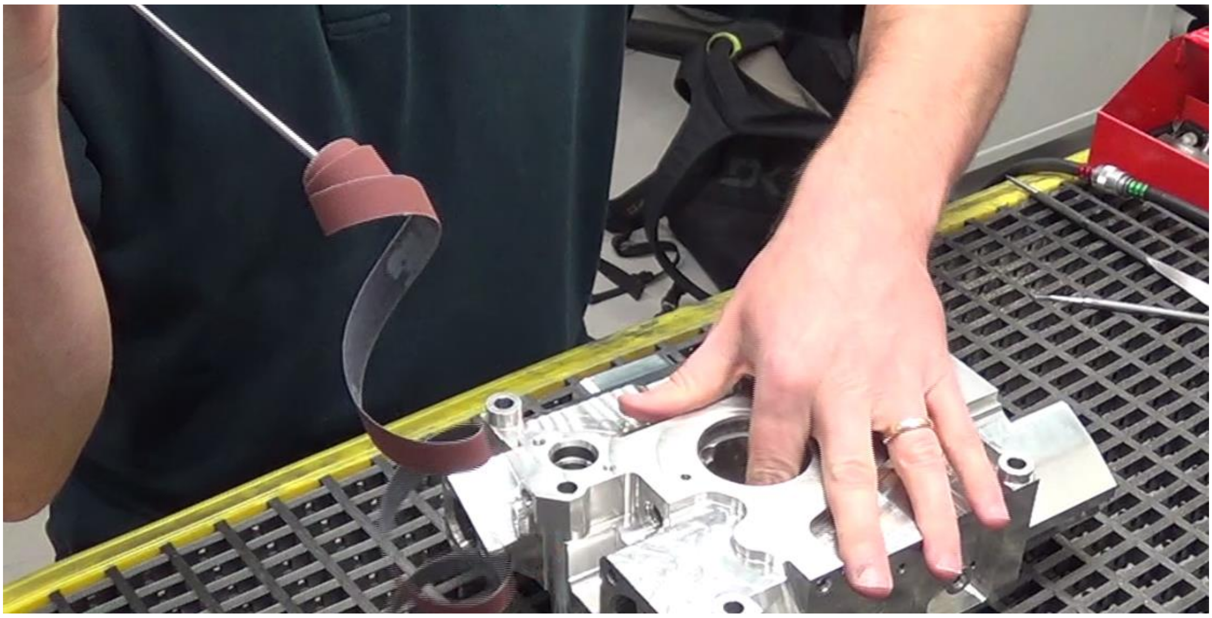


Figure 10-4: Deburring Process

The worker receives the parts after a machining process. Due to the tool speed of the machining process, the parts ought to go through the deburring process. The process aims are considered achieved, when all the burrs are removed from the part edges, the part is washed and cleaned, as well as sent to an inspection process. For the specific component, any feature change would negatively affect the functionality of the processed part

The features vary in terms of size, ranging from millimeters to a few centimeters. A single worker spends four to six hours per component. The work-cell contains a set of tools: two air compressed tools (one rotational and one blower), a tiny torch with light intensity regulator, a magnifying glass and different types of emery cloth, coarse files, needle files and fettling tools. In addition to that, two tubular lights are employed to provide extra illumination to the cell work while the operator works sitting facing the station.

Threaded Fastener Assembly

Threaded fastener assembly is a process which picks up a threaded screw of a determined size and moves the object towards a specific position, where the target hole has been identified. The threaded fastener assembly process should work based on any size of screws and match the screw size with the drilled hole size.

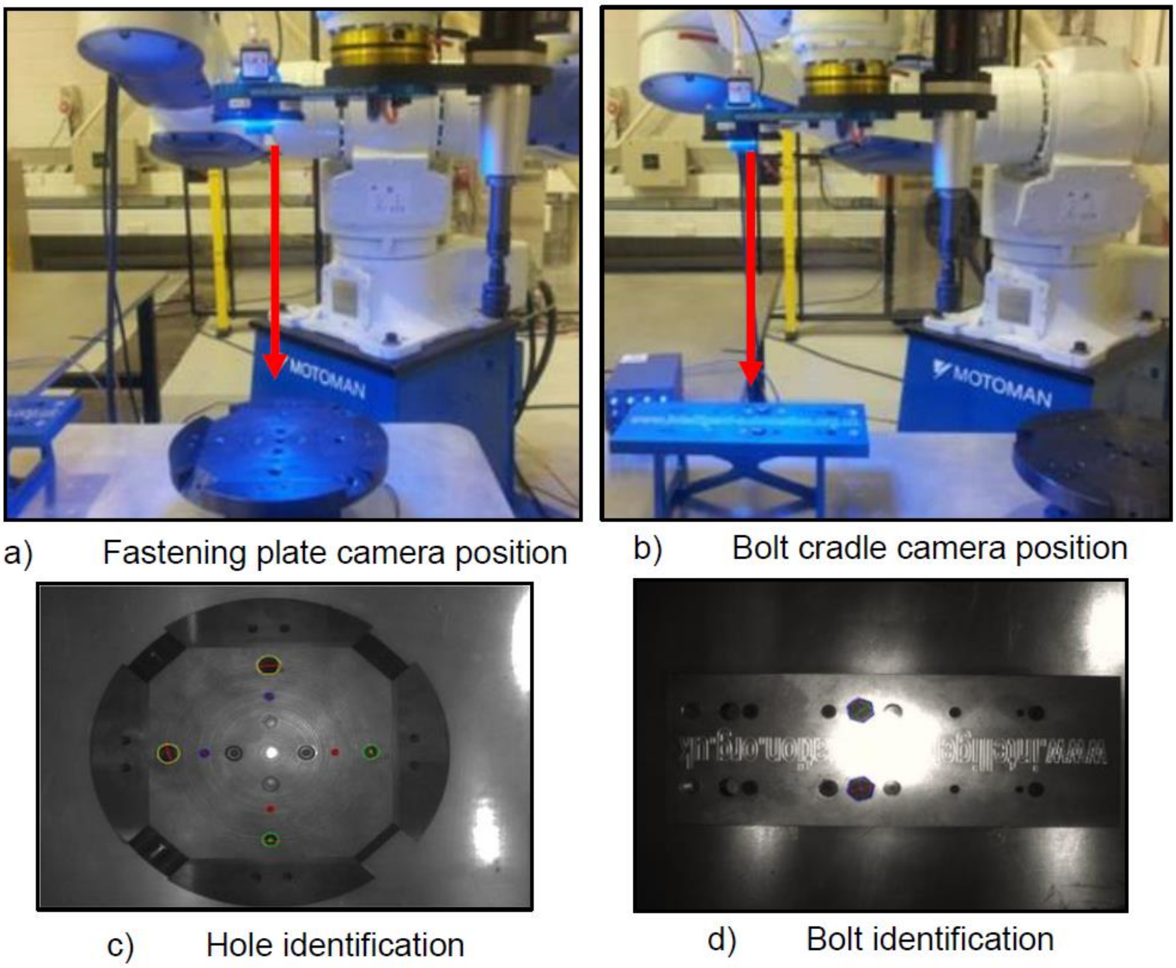


Figure 10-5: Threaded Fastener Assembly

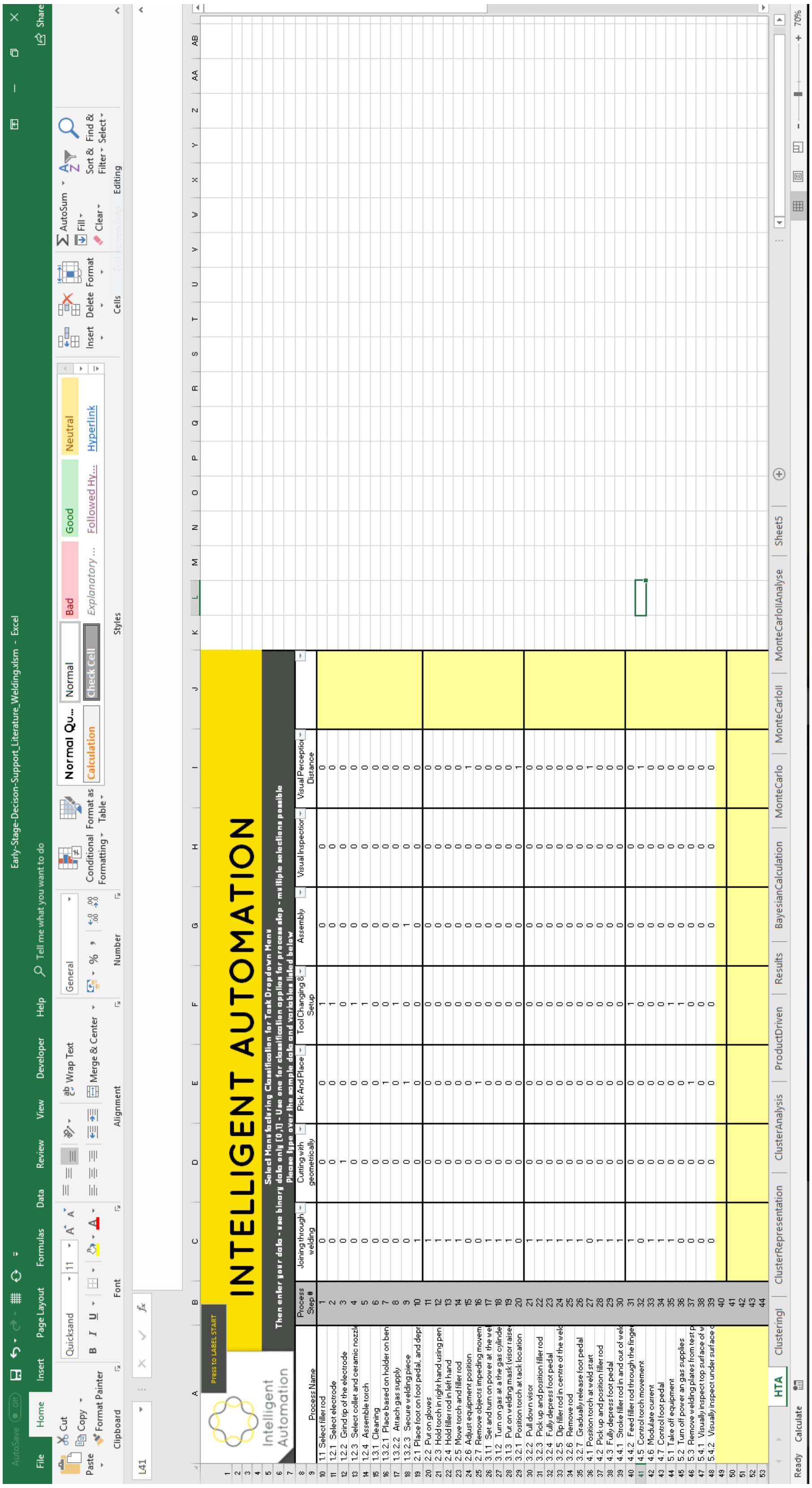
Based on such a match, the screw can be carefully inserted and rotated to assembly the screw into the threaded hole. Even though the process is comparatively easy for an operator, is requires certain capabilities from the intelligent automation systems in terms of visual and haptic perception.

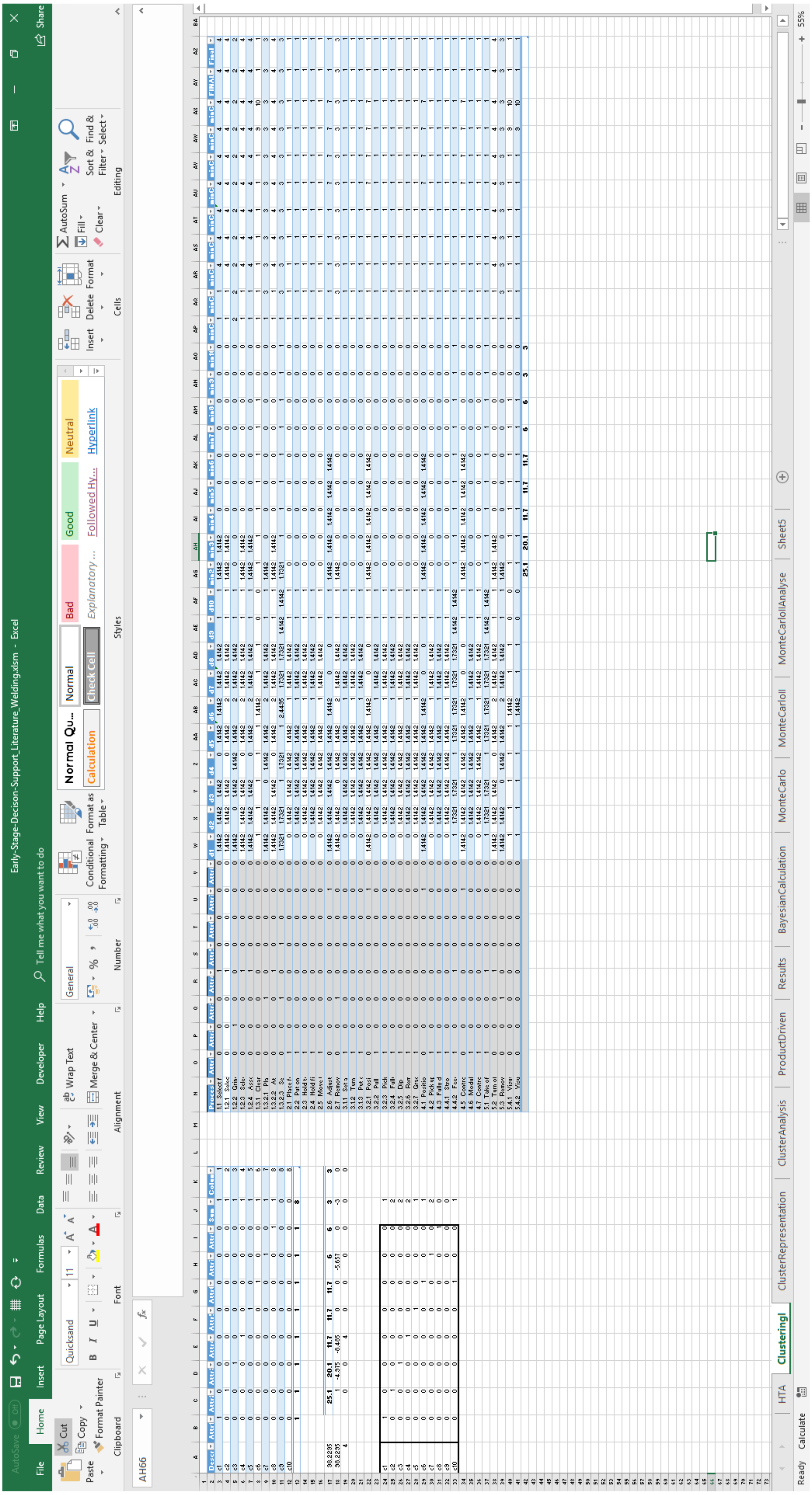
APPENDIX C

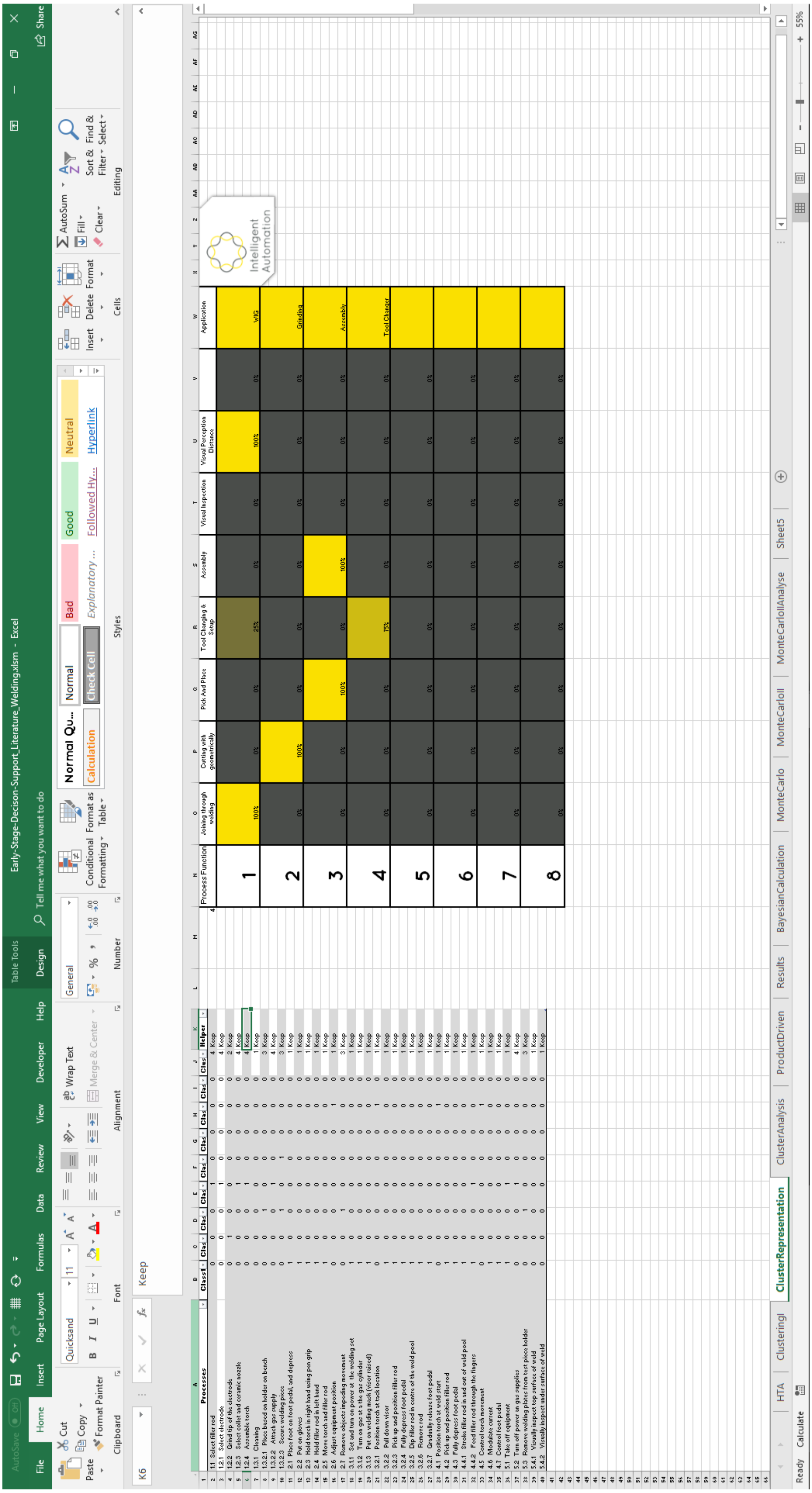
Attribute	*Attribute*	*Standard*
Changing material characteristics through transfer of particle	a1	DIN 8580
Changing material characteristics through particle screening out	a2	DIN 8580
Changing material characteristics through particle insertion	a3	DIN 8580
Coating from a gaseous or vaporous state	a4	DIN 8580
Coating from a liquid or mushy state	a5	DIN 8580
Coating from ionised state through electrolytic or chemical separation	a6	DIN 8580
Coating from a solid or powdery state	a7	DIN 8580
Pick and Place	a8	DIN 8593-1
Filling (e.g. impregnating)	a9	DIN 8593-2
Pressing in and on (e.g. screwing/rivetting)	a10	DIN 8593-3
Joining through primary shaping (e.g. grouting)	a11	DIN 8593-4
Joining through forming (e.g. seaming)	a12	DIN 8593-5
Joining through welding (e.g. Laser-, WIG- Welding)	a13	DIN 8593-6
Joining through soldering	a14	DIN 8593-7
Gluing	a15	DIN 8593-8
Textile Joining	a16	DIN 8593-9
Severing	a17	DIN 8588
Cutting with geometrically defined cutting edges	a18	DIN 8589
Cutting with geometrically undefined cutting edges	a19	DIN 8580
Removal operations	a20	DIN 8590
Disassembling	a21	DIN 8590
Cleaning	a22	DIN 8592
Forming under compressive conditions	a23	DIN 8583
Forming under compressive and tensile conditions	a24	DIN 8584
Forming under tensile conditions	a25	DIN 8585
Forming by bending	a26	DIN 8586
Forming under shearing conditions	a27	DIN 8587
Primary shaping from liquid state	a28	DIN 8581
Primary shaping from plastic state	a29	DIN 8581
Primary shaping from mushy state	a30	DIN 8581
Primary shaping from powdery or granular state	a31	DIN 8581
Primary shaping from fibrous or filamentary state	a32	DIN 8581
Primary shaping from gaseous or vaporous state	a33	DIN 8581
Primary shaping from ionised state	a34	DIN 8581
Tactile Perception Texture	a35	EXTENSION
Tactile Perception Counterforce	a36	EXTENSION
Tactile Perception Temperature	a37	EXTENSION
Tactile Perception Object Shape	a38	EXTENSION
Visual Perception Colours	a39	EXTENSION
Visual Perception Object Shape	a40	EXTENSION
Visual Perception Distance	a41	EXTENSION
Visual Perception Speed	a42	EXTENSION
Visual Perception Texture	a43	EXTENSION
Tool Changing and Setup	a44	EXTENSION
Labeling	a45	EXTENSION

APPENDIX D

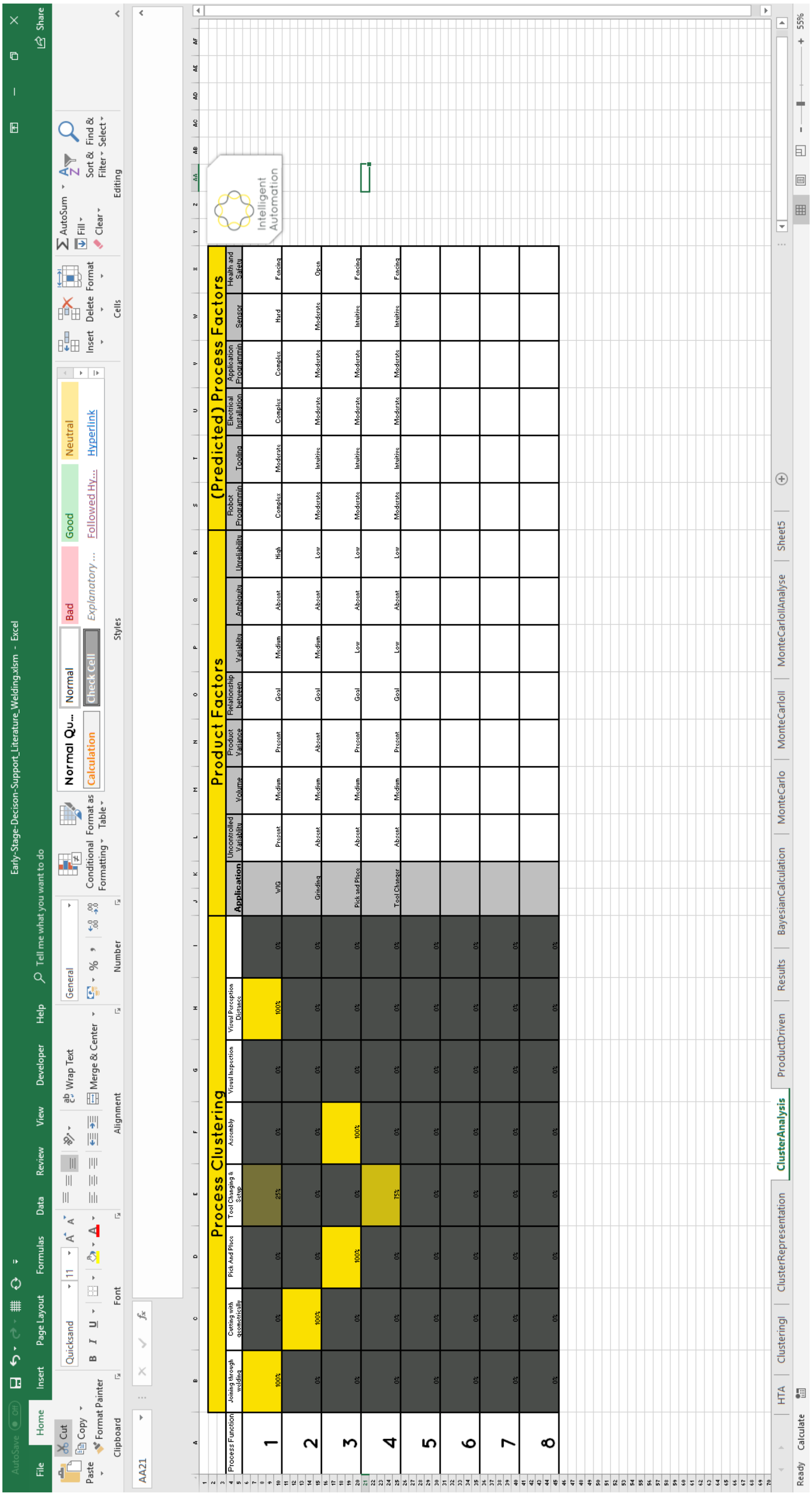
Toolbox Sheets for Task Complexity Framework



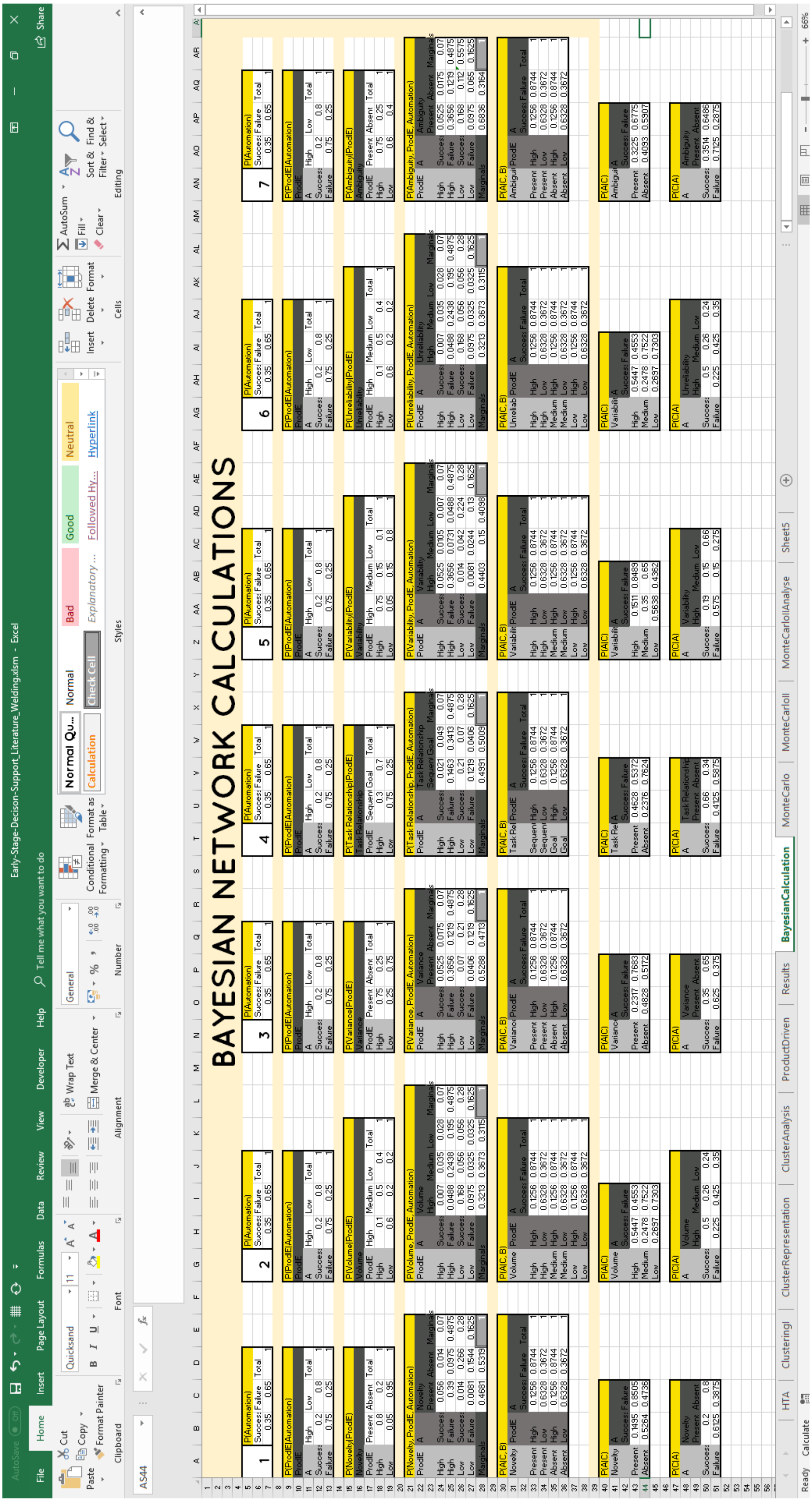

Early-Stage-Decision-Support_Literature_Welding.xlsm - Excel
HTA
Clustering
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5

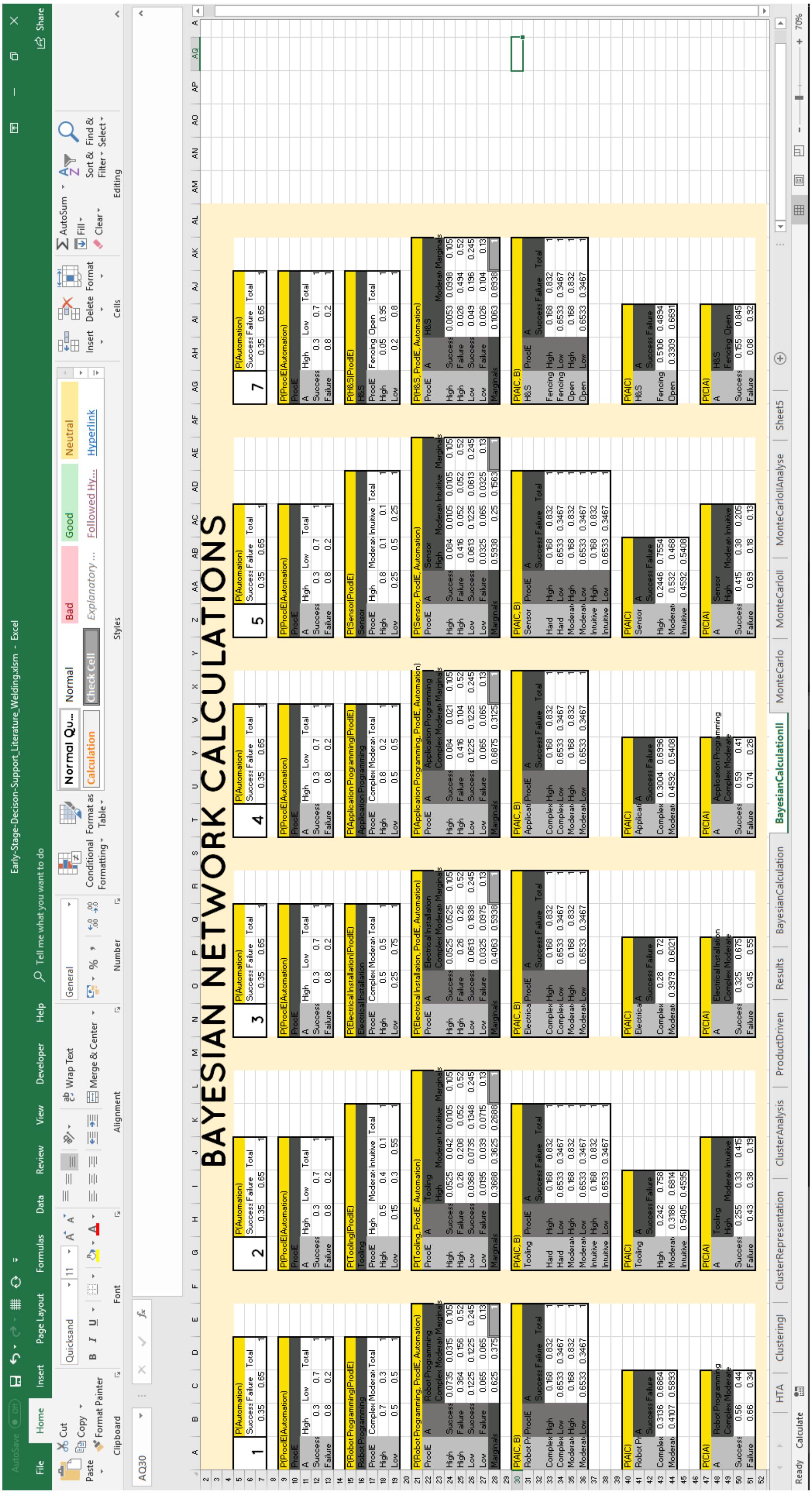


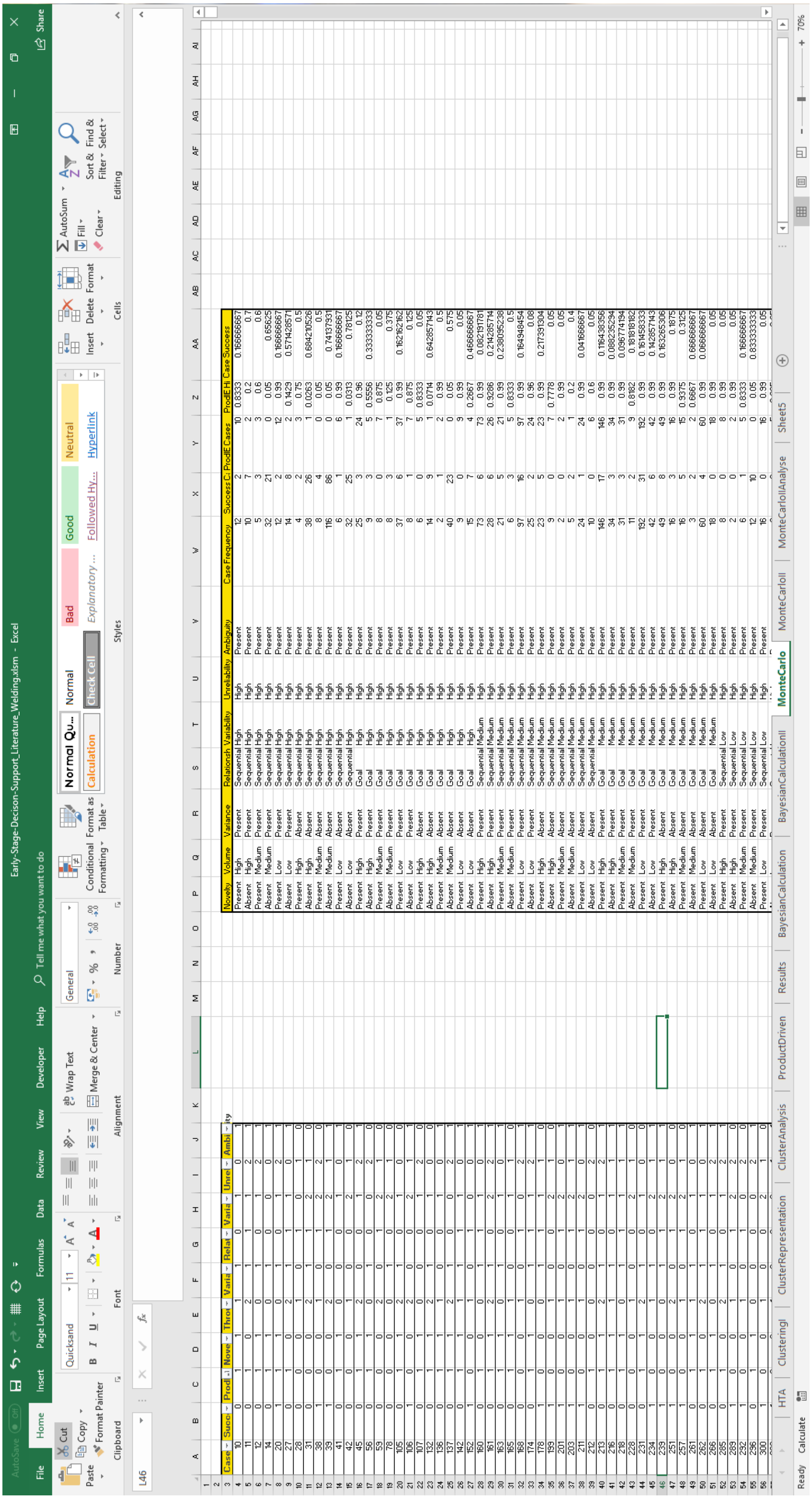
Early-Stage-Decison-Support_Literature_Welding.xlsm - Excel
Table Tools
File
Home
Insert
Page Layout
Formulas
Data
Review
View
Developer
Help
Design
Tell me what you want to do
Share
Keep
Processes
Helper
Process Function
Joining through welding
Cutting with geometrically
Pick And Place
Tool Changing & Setup
Assembly
Visual Inspection
Visual Perception Distance
Application
WIG
Grinding
Assembly
Tool Changer
Intelligent Automation
HTA
ClusteringI
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5
Ready
Calculate

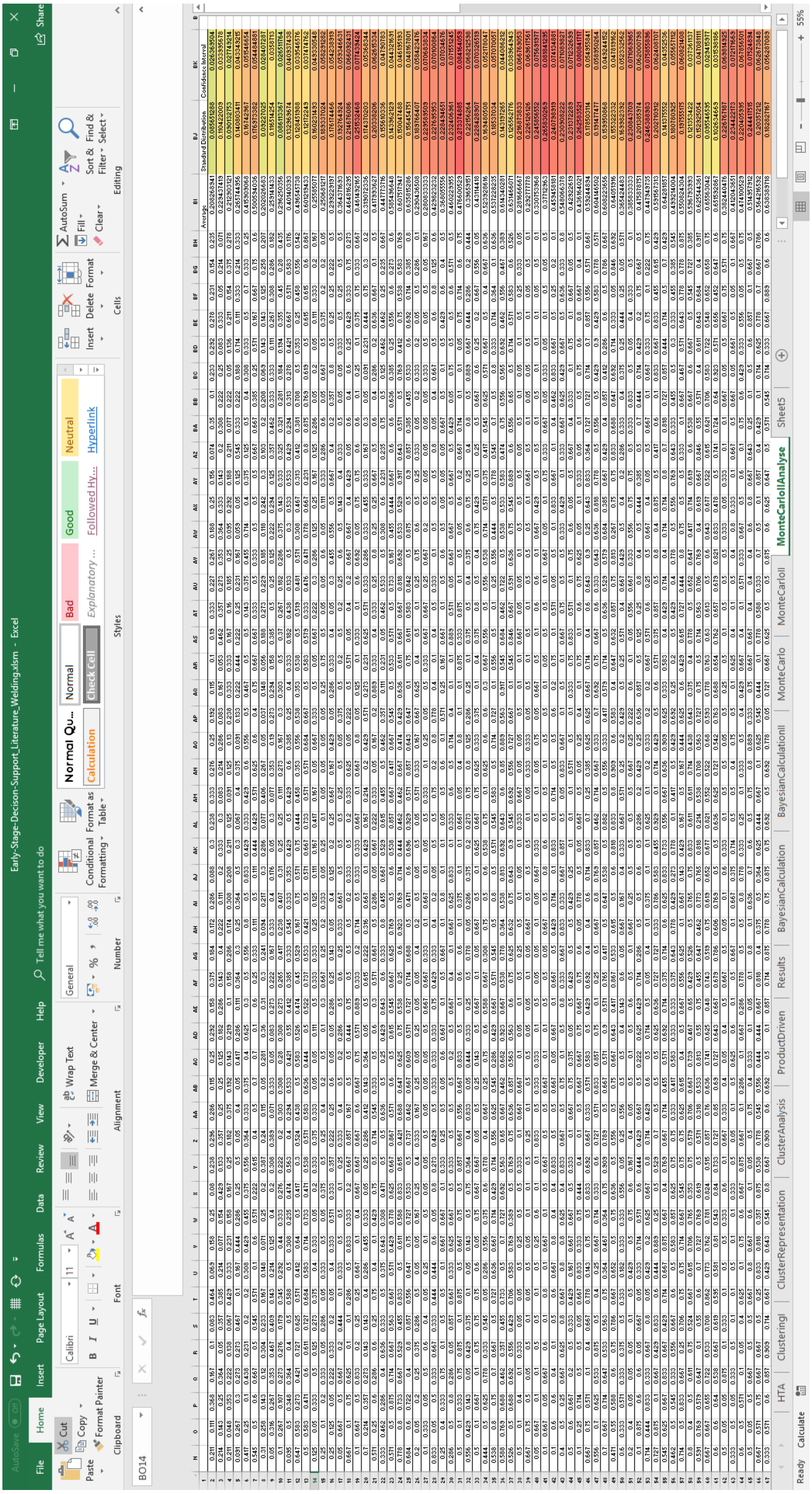


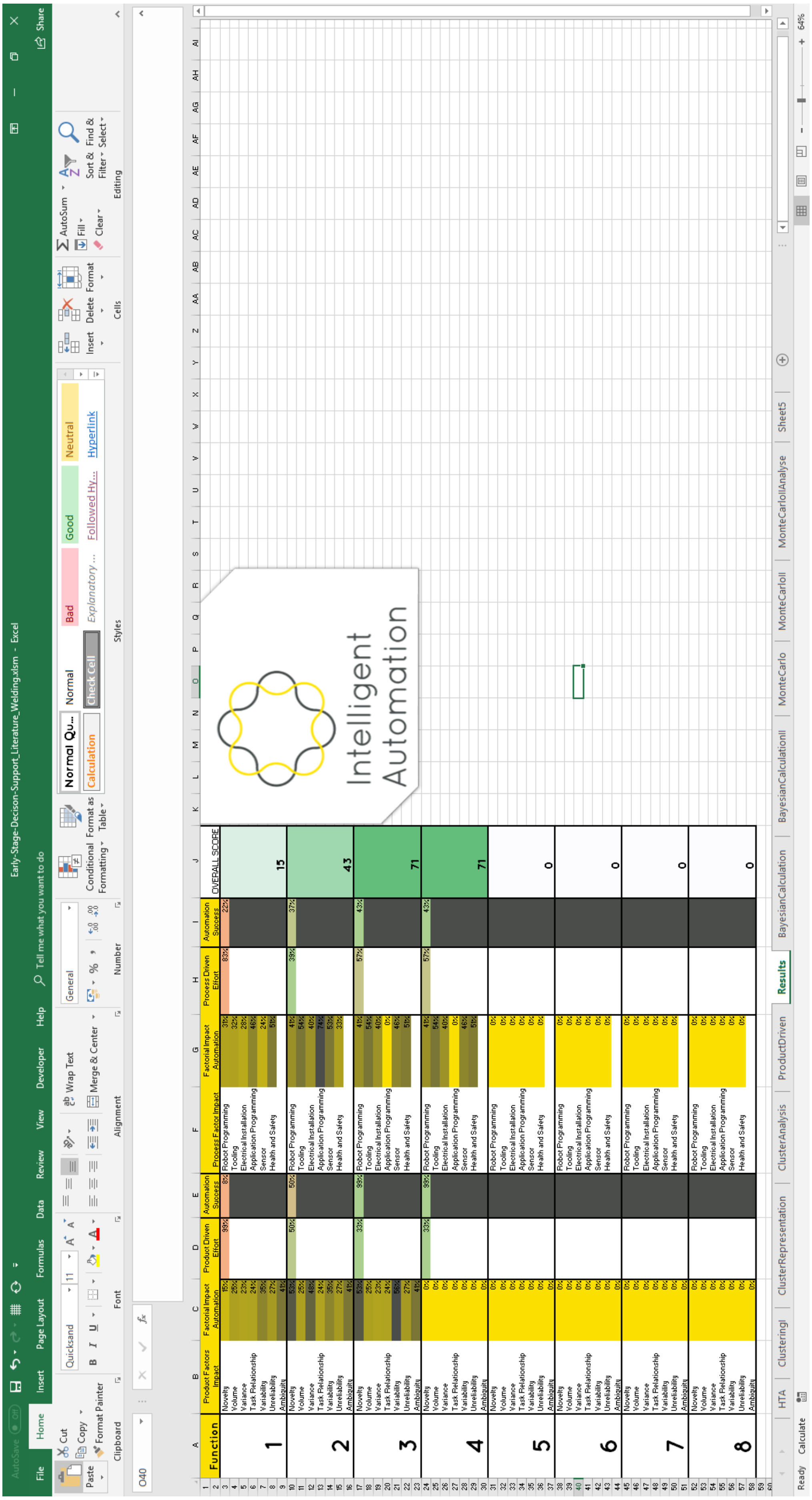
Early-Stage-Decision-Support_Literature_Welding.xlsm - Excel
Process Clustering
Product Factors
(Predicted) Process Factors
Process Function
Application
MIG
Grinding
Pick and Place
Tool Changer
Intelligent Automation
HTA
ClusteringI
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5


BAYESIAN NETWORK CALCULATIONS


Early-Stage-Decison-Support_Literature_Welding.xlsm - Excel
BAYESIAN NETWORK CALCULATIONS
HTA
ClusteringI
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
BayesianCalculationII
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5


Early-Stage-Decison-Support_Literature_Welding.xlsm - Excel
File
Home
Insert
Page Layout
Formulas
Data
Review
View
Developer
Help
Tell me what you want to do
Share
Clipboard
Font
Alignment
Number
Styles
Cells
Editing
Normal
Bad
Good
Neutral
Calculation
Check Cell
Explanatory ...
Followed Hy...
Hyperlink
Conditional Formatting
Format as Table
Insert
Delete
Format
AutoSum
Fill
Clear
Sort & Filter
Find & Select
L46
HTA
Clustering
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
BayesianCalculationII
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5
Ready
Calculate
70%


Early-Stage-Decison-Support_Literature_Welding.xlsm - Excel
HTA
Clustering
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
BayesianCalculationII
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5



Early-Stage-Decision-Support_Literature_Welding.xlsm - Excel
Intelligent Automation
Function
Product Factors Impact
Factorial Impact Automation
Product Driven Effort
Automation Success
Process Factor Impact
Process Driven Effort
OVERALL SCORE
15
43
71
71
0
0
0
0
HTA
ClusteringI
ClusterRepresentation
ClusterAnalysis
ProductDriven
Results
BayesianCalculation
BayesianCalculationII
MonteCarlo
MonteCarloII
MonteCarloIIAnalyse
Sheet5

Clustering

```
Public Sub SetupClustering()
'Delete Table Rows
    Sheets("ClusteringI").Visible = True
    Sheets("ClusteringI").Select
    Range("N5:AO5").Select
    Range(Selection, Selection.End(xlDown)).Select
'    For i = 1 To Range("ProcessTable").Rows.Count - 3
'    Selection.ListObject.ListRows(3).Delete
'    Next i

'Copy Names for calculation from HTA sheet
    Sheets("HTA").Select
    Worksheets("HTA").Range("A10").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
'Copy in first cluster
    Sheets("ClusteringI").Select
    Range("N3").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Range("N3").Select
' Exit copy mode
    Application.CutCopyMode = False
'End Sub

'Copy Data for calculation from HTA sheet
    Sheets("HTA").Select
    Worksheets("HTA").Range("C10").Select
    ActiveCell.Range("A1:H1").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
'Copy in first cluster
    Sheets("ClusteringI").Select
    Range("O3").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Range("O3").Select
' Exit copy mode
    Application.CutCopyMode = False

'FILL EMPTY CELLS ZERO
      Range("O3").Select
    ActiveCell.Range("A1:H1").Select
    Range(Selection, Selection.End(xlDown)).Select
    If IsEmpty(ActiveCell) Then
    Selection.SpecialCells(xlCellTypeBlanks).Select
```

```
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
    SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
    ReplaceFormat:=False
End If

' Clear_And_Fill_Centroids Macro
Range("CentroidsI[[Attr1]:[Attr8]]").Select
Application.CutCopyMode = False
Selection.ClearContents
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
    SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
    ReplaceFormat:=False
Range("B3").Select
ActiveCell.FormulaR1C1 = "1"
Range("C4").Select
ActiveCell.FormulaR1C1 = "1"
Range("D5").Select
ActiveCell.FormulaR1C1 = "1"
Range("E6").Select
ActiveCell.FormulaR1C1 = "1"
Range("F7").Select
ActiveCell.FormulaR1C1 = "1"
Range("G8").Select
ActiveCell.FormulaR1C1 = "1"
Range("H9").Select
ActiveCell.FormulaR1C1 = "1"
Range("I10").Select
ActiveCell.FormulaR1C1 = "1"

Range("CentroidsI").Select
Selection.NumberFormat = "0"

For i = 1 To 3

    Range("B3").Select
    ActiveCell.Range("A1:H9").Select
    Selection.Copy
    Range("B24").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
    Application.CutCopyMode = False

    Range("A17").Select
    ActiveCell.Range("A1").Select
    Selection.Copy
    Range("A18").Select
```

```
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
:=False, Transpose:=False
Application.CutCopyMode = False

 '==============================
 '2 Clusters
 '==============================

 SolverReset
 SolverOk SetCell:="$AG42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$4", _
    Engine:=3, EngineDesc:="Evolutionary"
 SolverOk SetCell:="$AG42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$4", _
    Engine:=3, EngineDesc:="Evolutionary"
 SolverAdd cellRef:=Range("J13"), _
 relation:=1, _
 formulaText:=39
 SolverAdd cellRef:=Range("K4"), _
 relation:=3, _
 formulaText:=2
 SolverAdd cellRef:=Range("B3:I12"), _
 relation:=5
 SolverSolve True

 Range("A17").Select
If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
  Range("B24:I33").Select
  Selection.Copy
  Range("CentroidsI[[Attr1]:[Attr8]]").Select
  Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
  Range("J16").Select
  Application.CutCopyMode = False

End If

 '==============================
 '3 Clusters
 '==============================
 SolverReset
 SolverOk SetCell:="$AH42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$5", _
    Engine:=3, EngineDesc:="Evolutionary"
 SolverOk SetCell:="$AH42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$5", _
    Engine:=3, EngineDesc:="Evolutionary"
 SolverAdd cellRef:=Range("J13"), _
```

```
    relation:=1, _
    formulaText:=39
    SolverAdd cellRef:=Range("K5"), _
    relation:=3, _
    formulaText:=2
    SolverAdd cellRef:=Range("B3:I12"), _
    relation:=5
    SolverSolve True

    Range("A17").Select
   If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
     Range("B24:I33").Select
     Selection.Copy
     Range("CentroidsI[[Attr1]:[Attr8]]").Select
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
     Range("J16").Select
     Application.CutCopyMode = False

   End If

    '=============================
    '4 Clusters
    '=============================
    SolverReset
    SolverOk SetCell:="$AI42", MaxMinVal:=2, ValueOf:=0, ByChange:="$B$3:$I$6", _
       Engine:=3, EngineDesc:="Evolutionary"
    SolverOk SetCell:="$AI42", MaxMinVal:=2, ValueOf:=0, ByChange:="$B$3:$I$6", _
       Engine:=3, EngineDesc:="Evolutionary"
    SolverAdd cellRef:=Range("J13"), _
    relation:=1, _
    formulaText:=39
    SolverAdd cellRef:=Range("K6"), _
    relation:=3, _
    formulaText:=2
    SolverAdd cellRef:=Range("B3:I12"), _
    relation:=5
    SolverSolve True

    Range("A17").Select
   If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
     Range("B24:I33").Select
     Selection.Copy
     Range("CentroidsI[[Attr1]:[Attr8]]").Select
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
```

```
    Range("J16").Select
    Application.CutCopyMode = False

  End If

   '==============================
   '5 Clusters
   '==============================
   SolverReset
   SolverOk SetCell:="$AJ42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$7", _
     Engine:=3, EngineDesc:="Evolutionary"
   SolverOk SetCell:="$AJ42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$7", _
     Engine:=3, EngineDesc:="Evolutionary"
   SolverAdd cellRef:=Range("J13"), _
   relation:=1, _
   formulaText:=39
   SolverAdd cellRef:=Range("K7"), _
   relation:=3, _
   formulaText:=2
   SolverAdd cellRef:=Range("B3:I12"), _
   relation:=5
   SolverSolve True

   Range("A17").Select
  If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
    Range("B24:I33").Select
    Selection.Copy
    Range("CentroidsI[[Attr1]:[Attr8]]").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
    Range("J16").Select
    Application.CutCopyMode = False

  End If

   '==============================
   '6 Clusters
   '==============================
   SolverReset
   SolverOk SetCell:="$AK42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$8", _
     Engine:=3, EngineDesc:="Evolutionary"
   SolverOk SetCell:="$AK42", MaxMinVal:=2, ValueOf:=0,
ByChange:="$B$3:$I$8", _
     Engine:=3, EngineDesc:="Evolutionary"
   SolverAdd cellRef:=Range("J13"), _
```

```
    relation:=1, _
    formulaText:=39
    SolverAdd cellRef:=Range("K8"), _
    relation:=3, _
    formulaText:=2
    SolverAdd cellRef:=Range("B3:I12"), _
    relation:=5
    SolverSolve True

     Range("A17").Select
   If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
     Range("B24:I33").Select
     Selection.Copy
     Range("CentroidsI[[Attr1]:[Attr8]]").Select
     Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
     Range("J16").Select
     Application.CutCopyMode = False

   End If

'     '============================
'     '7 Clusters
'     '============================
'     SolverReset
'                SolverOk   SetCell:="$AL42",   MaxMinVal:=2,   ValueOf:=0,
ByChange:="$B$3:$I$9", _
'          Engine:=3, EngineDesc:="Evolutionary"
'                SolverOk   SetCell:="$AL42",   MaxMinVal:=2,   ValueOf:=0,
ByChange:="$B$3:$I$9", _
'          Engine:=3, EngineDesc:="Evolutionary"
'     SolverAdd cellRef:=Range("J13"), _
'     relation:=1, _
'     formulaText:=39
'     SolverAdd cellRef:=Range("K9"), _
'     relation:=3, _
'     formulaText:=2
'     SolverAdd cellRef:=Range("B3:I12"), _
'     relation:=5
'     SolverSolve True
'
'      Range("A17").Select
'    If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
'      Range("B24:I33").Select
'      Selection.Copy
'      Range("CentroidsI[[Attr1]:[Attr8]]").Select
'      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
'          :=False, Transpose:=False
```

```
'           Range("J16").Select
'           Application.CutCopyMode = False
'
'       End If
'       '==============================
'       '8 Clusters
'       '==============================
'       SolverReset
'                          SolverOk    SetCell:="$AM42",    MaxMinVal:=2,    ValueOf:=0,
ByChange:="$B$3:$I$10", _
'           Engine:=3, EngineDesc:="Evolutionary"
'                          SolverOk    SetCell:="$AM42",    MaxMinVal:=2,    ValueOf:=0,
ByChange:="$B$3:$I$10", _
'           Engine:=3, EngineDesc:="Evolutionary"
'       SolverAdd cellRef:=Range("J13"), _
'       relation:=1, _
'       formulaText:=39
'       SolverAdd cellRef:=Range("K10"), _
'       relation:=3, _
'       formulaText:=2
'       SolverAdd cellRef:=Range("B3:I12"), _
'       relation:=5
'       SolverSolve True
'
'         Range("A17").Select
'       If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
'         Range("B24:I33").Select
'         Selection.Copy
'         Range("CentroidsI[[Attr1]:[Attr8]]").Select
'         Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
'             :=False, Transpose:=False
'         Range("J16").Select
'         Application.CutCopyMode = False
'
'       End If
'
'       '==============================
'       '9 Clusters
'       '==============================
'       SolverReset
'                          SolverOk    SetCell:="$AN42",    MaxMinVal:=2,    ValueOf:=0,
ByChange:="$B$3:$I$11", _
'           Engine:=3, EngineDesc:="Evolutionary"
'                          SolverOk    SetCell:="$AN42",    MaxMinVal:=2,    ValueOf:=0,
ByChange:="$B$3:$I$11", _
'           Engine:=3, EngineDesc:="Evolutionary"
'       SolverAdd cellRef:=Range("J13"), _
'       relation:=1, _
```

```
'         formulaText:=39
'         SolverAdd cellRef:=Range("K11"), _
'         relation:=3, _
'         formulaText:=2
'         SolverAdd cellRef:=Range("B3:I12"), _
'         relation:=5
'         SolverSolve True
'
'           Range("A17").Select
'       If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
'           Range("B24:I33").Select
'           Selection.Copy
'           Range("CentroidsI[[Attr1]:[Attr8]]").Select
'           Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
'               :=False, Transpose:=False
'           Range("J16").Select
'           Application.CutCopyMode = False
'
'       End If
'
'         '============================
'         '10 Clusters
'         '============================
'         SolverReset
'                             SolverOk    SetCell:="$AO42",    MaxMinVal:=2,    ValueOf:=0,
ByChange:="$B$3:$I$12", _
'             Engine:=3, EngineDesc:="Evolutionary"
'                             SolverOk    SetCell:="$AO42",    MaxMinVal:=2,    ValueOf:=0,
ByChange:="$B$3:$I$12", _
'             Engine:=3, EngineDesc:="Evolutionary"
'         SolverAdd cellRef:=Range("J13"), _
'         relation:=1, _
'         formulaText:=39
'         SolverAdd cellRef:=Range("K12"), _
'         relation:=3, _
'         formulaText:=2
'         SolverAdd cellRef:=Range("B3:I12"), _
'         relation:=5
'         SolverSolve True
'
        Range("A17").Select
        If ActiveCell.Value > ActiveCell.Offset(1, 0).Value Then
            Range("B24:I33").Select
            Selection.Copy
            Range("CentroidsI[[Attr1]:[Attr8]]").Select
            Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
                :=False, Transpose:=False
            Range("J16").Select
```

```
        Application.CutCopyMode = False

      End If

    Next i

    MsgBox ("Please click on the Clustering Sheet for further instructions.")
    Sheets("MonteCarloII").Visible = False
    Sheets("MonteCarloII").Visible = False

'ClusterRepresentation Table1
    Worksheets("ClusterRepresentation").Activate
    Range("A2:K2").Select
    Range(Selection, Selection.End(xlDown)).Select
    For i = 1 To Range("FinalCluster").Rows.Count - 2
    Selection.ListObject.ListRows(3).Delete
    Next i

' Cluster Representation
    Worksheets("ClusteringI").Activate
    Worksheets("ClusteringI").Range("A19").Activate

' Paste relevant cluster
    Sheets("ClusteringI").Select
    Range("N3").Select
    ActiveCell.Range("A1:I1").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False

    Sheets("ClusteringI").Select
    Range("AZ3").Select
    ActiveCell.Range("A1").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("J2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False

    Range("A2:J2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues
    Application.CutCopyMode = False
```

```
'   'Fill Blank Centroids with 100
'   Range("A2:I2").Select
'   Range(Selection, Selection.End(xlDown)).Select
'   If IsEmpty(ActiveCell) Then
'       Selection.SpecialCells(xlCellTypeBlanks).Select
'       Selection.Replace What:="", Replacement:="100", LookAt:=xlPart, _
'       SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
'       ReplaceFormat:=False
'   End If

    'Fill Blank Sequence Helpers with Keep
    Range("K3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.SpecialCells(xlCellTypeBlanks).Select
    Selection.Replace What:="", Replacement:="Keep", LookAt:=xlPart, _
        SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
        ReplaceFormat:=False
    'Copy Cluster Names
    Range("Q1").Select
    Sheets("HTA").Select
    Range("C8:J9").Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("O1").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Range("R8").Select
    Range("O1:V2").Select
    With Selection.Validation
        .Delete
        .Add Type:=xlValidateInputOnly, AlertStyle:=xlValidAlertStop, Operator _
        :=xlBetween
        .IgnoreBlank = True
        .InCellDropdown = True
        .ShowInput = True
        .ShowError = True
    End With
    ActiveWorkbook.Save
End Sub
```

Cluster Representation

```
Sub Clustering()

'ClusterRepresentation Table1
    Worksheets("ClusterRepresentation").Activate
    Range("A2:K2").Select
    Range(Selection, Selection.End(xlDown)).Select
```

```
    For i = 1 To Range("FinalCluster").Rows.Count - 2
    Selection.ListObject.ListRows(3).Delete
    Next i

' Cluster Representation
    Worksheets("ClusteringI").Activate
    Worksheets("ClusteringI").Range("A19").Activate

' Paste relevant cluster
    Sheets("ClusteringI").Select
    Range("N3").Select
    ActiveCell.Range("A1:I1").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False

    Sheets("ClusteringI").Select
    Range("AZ3").Select
    ActiveCell.Range("A1").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("J2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False

    Range("A2:J2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues
    Application.CutCopyMode = False
    'Fill Blank Centroids with 100
    Range("A2:I2").Select
    Range(Selection, Selection.End(xlDown)).Select
    If IsEmpty(ActiveCell) Then
        Selection.SpecialCells(xlCellTypeBlanks).Select
        Selection.Replace What:="", Replacement:="100", LookAt:=xlPart, _
        SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
        ReplaceFormat:=False
    End If

    'Fill Blank Sequence Helpers with Keep
    Range("K3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.SpecialCells(xlCellTypeBlanks).Select
```

```
    Selection.Replace What:="", Replacement:="Keep", LookAt:=xlPart, _
        SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
        ReplaceFormat:=False
    'Copy Cluster Names
    Range("Q1").Select
    Sheets("HTA").Select
    Range("C8:J9").Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("O1").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Range("R8").Select
    Range("O1:V2").Select
    With Selection.Validation
        .Delete
        .Add Type:=xlValidateInputOnly, AlertStyle:=xlValidAlertStop, Operator _
        :=xlBetween
        .IgnoreBlank = True
        .InCellDropdown = True
        .ShowInput = True
        .ShowError = True
    End With
    ActiveWorkbook.Save
End Sub
```

Create Task Functions

```
Sub Solver_Solve_Minimum_SSE_Macro()
    ' Make Content Zero
    Range("Centroids[[C_Field1]:[C_Field8]]").Select
    Selection.ClearContents
    Range("Centroids[[C_Field1]:[C_Field8]]").Select
    Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
        SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
        ReplaceFormat:=False
    ' Initialise Centroids
    Range("BY3").Select
    ActiveCell.FormulaR1C1 = "=MAX(ProcessTable[Attr1])"
    ActiveCell.Offset(1, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=MAX(ProcessTable[Attr2])"
    ActiveCell.Offset(1, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=MAX(ProcessTable[Attr3])"
    ActiveCell.Offset(1, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=MAX(ProcessTable[Attr4])"
    ActiveCell.Offset(1, 1).Range("A1").Select
    ActiveCell.FormulaR1C1 = "=MAX(ProcessTable[Attr5])"
    ' Solver_Solve_Minimum_SSE Macro
```

```
    SolverReset
    SolverOk SetCell:="$BX$16", MaxMinVal:=2, ValueOf:=0,
ByChange:="$BY$3:$CF$7", _
        Engine:=3, EngineDesc:="Evolutionary"
    SolverOk SetCell:="$BX$16", MaxMinVal:=2, ValueOf:=0,
ByChange:="$BY$3:$CF$7", _
        Engine:=3, EngineDesc:="Evolutionary"
    SolverAdd cellRef:=Range("F4:F6"), _
    relation:=1, _
    formulaText:=1
    SolverAdd cellRef:=Range("C4:E6"), _
    relation:=3, _
    formulaText:=39
    SolverAdd cellRef:=Range("BY3:CF7"), _
    relation:=5
    SolverSolve True

'ClusterRepresentation Table1
    Worksheets("ClusterRepresentation").Activate
    Range("A2:P2").Select
    Range(Selection, Selection.End(xlDown)).Select
    For i = 1 To Range("FinalCluster").Rows.Count - 2
    Selection.ListObject.ListRows(3).Delete
    Next i

' Cluster Representation
    Worksheets("Clustering").Activate
    Worksheets("Clustering").Range("BZ16").Activate

' Paste relevant cluster
    If ActiveCell.Value = 1 Then
        Sheets("Clustering").Select
        Range("A1").Select
        ActiveCell.Range("A3:J3").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Sheets("ClusterRepresentation").Select
        Range("A2").Select
        ActiveSheet.Paste
        Application.CutCopyMode = False
    ElseIf ActiveCell.Value = 2 Then
        Sheets("Clustering").Select
        Range("N3").Select
        ActiveCell.Range("A3:K3").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Sheets("ClusterRepresentation").Select
        Range("A2").Select
```

```
    ActiveSheet.Paste
    Application.CutCopyMode = False
ElseIf ActiveCell.Value = 3 Then
    Sheets("Clustering").Select
    Range("AB1").Select
    ActiveCell.Range("A3:L3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
ElseIf ActiveCell.Value = 4 Then
    Sheets("Clustering").Select
    Range("AQ3").Select
    ActiveCell.Range("A3:M3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
ElseIf ActiveCell.Value = 5 Then
    Sheets("Clustering").Select
    Range("BG3").Select
    ActiveCell.Range("A3:N3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("A2").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
End If

Selection.Copy
Selection.PasteSpecial Paste:=xlPasteValues
Application.CutCopyMode = False
'Fill Blank Centroids with 100
Range("A2:O2").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="100", LookAt:=xlPart, _
    SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
    ReplaceFormat:=False
'Fill Blank Sequence Helpers with Keep
Range("P3").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.SpecialCells(xlCellTypeBlanks).Select
```

```
    Selection.Replace What:="", Replacement:="Keep", LookAt:=xlPart, _
        SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
        ReplaceFormat:=False
    'Copy Cluster Names
    Range("Q1").Select
    Sheets("HTA").Select
    Range("C8:J9").Select
    Selection.Copy
    Sheets("ClusterRepresentation").Select
    Range("T1").Select
    ActiveSheet.Paste
    Application.CutCopyMode = False
    Range("R8").Select
    Range("S1:AA2").Select
    With Selection.Validation
        .Delete
        .Add Type:=xlValidateInputOnly, AlertStyle:=xlValidAlertStop, Operator _
        :=xlBetween
        .IgnoreBlank = True
        .InCellDropdown = True
        .ShowInput = True
        .ShowError = True
    End With
    ActiveWorkbook.Save

MsgBox ("Please click on the ClusterRepresentation Sheet for further instructions.")

End Sub
```

Monte Carlo Sampling

```
Sub ResultCalculation()
'Unhide Sheets
    Sheets("MonteCarlo").Visible = True
    Sheets("MonteCarloII").Visible = True
    For i = 1 To 180
    ' Monte Carlos Simulation of Factor Dependencies
        Sheets("MonteCarlo").Select
    'Define ProdIE
        Range("Table4[Success]").Select
        Selection.Value = "=discretesim(1,0,,,,,0.35,0.65,,,,)"
        Range("B4").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Application.CutCopyMode = False
        ActiveWorkbook.Save
```

```
   Range("C4").Select
Do Until IsEmpty(ActiveCell.Offset(0, -2).Value)
      If (ActiveCell.Offset(0, -1).Range("A1").Value = 1) Then
         ActiveCell.Value = "=discretesim(1,0,,,,,0.2,0.8,,,,)"
         ActiveCell.Offset(1, 0).Select
      Else
         ActiveCell.Value = "=discretesim(1,0,,,,,0.75,0.25,,,,)"
         ActiveCell.Offset(1, 0).Select
      End If
Loop
   Range("C4").Select
   Range(Selection, Selection.End(xlDown)).Select
   Selection.Copy
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Application.CutCopyMode = False
   ActiveWorkbook.Save
   Range("D4").Select

'Define Novelty
Do Until IsEmpty(ActiveCell.Offset(0, -3).Value)
      If (ActiveCell.Offset(0, -1).Range("A1").Value = 1) Then
         ActiveCell.Value = "=discretesim(1,0,,,,,0.8,0.2,,,,)"
         ActiveCell.Offset(1, 0).Select
      Else
         ActiveCell.Value = "=discretesim(1,0,,,,,0.05,0.95,,,,)"
         ActiveCell.Offset(1, 0).Select
      End If
Loop
   Range("D4").Select
   Range(Selection, Selection.End(xlDown)).Select
   Selection.Copy
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Application.CutCopyMode = False
   ActiveWorkbook.Save
   Range("E4").Select

'Define Volume
Do Until IsEmpty(ActiveCell.Offset(0, -4).Value)
      If (ActiveCell.Offset(0, -2).Range("A1").Value = 1) Then
         ActiveCell.Value = "=discretesim(1,0,2,,,,0.1,0.5,0.4,,,)"
         ActiveCell.Offset(1, 0).Select
      Else
         ActiveCell.Value = "=discretesim(1,0,2,,,,0.6,0.2,0.2,,,)"
         ActiveCell.Offset(1, 0).Select
      End If
Loop
```

```
    Range("E4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("F4").Select

'Define Variance
Do Until IsEmpty(ActiveCell.Offset(0, -5).Value)
        If (ActiveCell.Offset(0, -3).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,,,,,0.75,0.25,,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,,,,,0.25,0.75,,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("F4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("G4").Select

'Define Task Relationship
Do Until IsEmpty(ActiveCell.Offset(0, -6).Value)
        If (ActiveCell.Offset(0, -4).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,,,,,0.3,0.7,,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,,,,,0.75,0.25,,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("G4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("H4").Select

'Define Variability
```

```
Do Until IsEmpty(ActiveCell.Offset(0, -7).Value)
        If (ActiveCell.Offset(0, -5).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.75,0.15,0.1,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.05,0.15,0.8,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("H4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("I4").Select

'Define Unreliability
Do Until IsEmpty(ActiveCell.Offset(0, -8).Value)
        If (ActiveCell.Offset(0, -6).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.1,0.5,0.4,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.6,0.2,0.2,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("I4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("J4").Select

'Define Ambiguity
Do Until IsEmpty(ActiveCell.Offset(0, -9).Value)
        If (ActiveCell.Offset(0, -7).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,,,,,0.75,0.25,,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,,,,,0.6,0.4,,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("J4").Select
```

```
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Application.CutCopyMode = False
        ActiveWorkbook.Save

        Range("AA4").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        ActiveCell.Offset(0, i).Range("A1").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
        Application.CutCopyMode = False

    Next i

    ' Updating the results for Sheet1 to show results
        ActiveWorkbook.Save
        Sheets("ClusterAnalysis").Select
        Range("L6").Select

'FIRST CLUSTER
    If IsEmpty(ActiveCell) Then

    Range("L11").Select
    Else
        Sheets("MonteCarlo").Select
        Range("V4").Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
```

```
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, 10).Range("A1:B1").Select
        Selection.Copy
        Sheets("Sheet1").Select
        Range("D3").Select
            Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Sheets("ClusterAnalysis").Select
        Range("L11").Select
    End If


'SECOND CLUSTER
    If IsEmpty(ActiveCell) Then

    Range("L16").Select
    Else
        Sheets("MonteCarlo").Select
        Range("V4").Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q11").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R11").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P11").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("D10").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L16").Select
End If

'THIRD CLUSTER
If IsEmpty(ActiveCell) Then

Range("L21").Select
Else
   Sheets("MonteCarlo").Select
   Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P16").Value)
```

```
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("D17").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L21").Select
End If

'FOURTH CLUSTER
   If IsEmpty(ActiveCell) Then

Range("L26").Select
Else
   Sheets("MonteCarlo").Select
   Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
```

```
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, 10).Range("A1:B1").Select
    Selection.Copy
    Sheets("Sheet1").Select
    Range("D24").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Sheets("ClusterAnalysis").Select
    Range("L26").Select
End If

'FIFTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("L31").Select
Else
    Sheets("MonteCarlo").Select
    Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q26").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("D31").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L31").Select
End If

'SIXTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("L36").Select
Else
   Sheets("MonteCarlo").Select
   Range("V4").Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("D38").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L36").Select
 End If

'SEVENTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("L41").Select
```

```
Else
   Sheets("MonteCarlo").Select
   Range("V7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("D45").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L41").Select
End If

'EIGHTH CLUSTER
```

```
If IsEmpty(ActiveCell) Then
   Sheets("Sheet1").Select
   Range("A1").Select
Else
   Sheets("MonteCarlo").Select
   Range("V7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("D52").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("Sheet1").Select
```

```
        Range("A1").Select
    End If

' Monte Carlos Simulation of Factor Dependencies of the second Monte Carlo
    Sheets("MonteCarloII").Select
For i = 1 To 180
    'Define ProcIE
        Range("Table5[Success]").Select
        Selection.Value = "=discretesim(1,0,,,,,0.35,0.65,,,,)"
        Range("B4").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Application.CutCopyMode = False
        ActiveWorkbook.Save
        Range("C4").Select
    Do Until IsEmpty(ActiveCell.Offset(0, -2).Value)
            If (ActiveCell.Offset(0, -1).Range("A1").Value = 1) Then
                ActiveCell.Value = "=discretesim(1,0,,,,,0.3,0.7,,,,)"
                ActiveCell.Offset(1, 0).Select
            Else
                ActiveCell.Value = "=discretesim(1,0,,,,,0.8,0.2,,,,)"
                ActiveCell.Offset(1, 0).Select
            End If
    Loop
        Range("C4").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Application.CutCopyMode = False
        ActiveWorkbook.Save
        Range("D4").Select

    'Define Robot Programming
    Do Until IsEmpty(ActiveCell.Offset(0, -3).Value)
            If (ActiveCell.Offset(0, -1).Range("A1").Value = 1) Then
                ActiveCell.Value = "=discretesim(1,0,,,,,0.7,0.3,,,,)"
                ActiveCell.Offset(1, 0).Select
            Else
                ActiveCell.Value = "=discretesim(1,0,,,,,0.5,0.5,,,,)"
                ActiveCell.Offset(1, 0).Select
            End If
    Loop
        Range("D4").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
```

```
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("E4").Select

'Define Tooling
Do Until IsEmpty(ActiveCell.Offset(0, -4).Value)
        If (ActiveCell.Offset(0, -2).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.4,0.1,0.5,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.3,0.55,0.15,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("E4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("F4").Select

'Define Electrical Installation
Do Until IsEmpty(ActiveCell.Offset(0, -5).Value)
        If (ActiveCell.Offset(0, -3).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,,,,,0.5,0.5,,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,,,,,0.25,0.75,,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("F4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("G4").Select

'Define Application Programming
Do Until IsEmpty(ActiveCell.Offset(0, -6).Value)
        If (ActiveCell.Offset(0, -4).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,,,,,0.8,0.2,,,,)"
```

```
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,,,,,0.5,0.5,,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("G4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("H4").Select

'Define Sensor
Do Until IsEmpty(ActiveCell.Offset(0, -7).Value)
        If (ActiveCell.Offset(0, -5).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.1,0.1,0.8,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,2,,,,0.25,0.5,0.25,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("H4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Application.CutCopyMode = False
    ActiveWorkbook.Save
    Range("I4").Select

'Define Health and Safety
Do Until IsEmpty(ActiveCell.Offset(0, -8).Value)
        If (ActiveCell.Offset(0, -6).Range("A1").Value = 1) Then
            ActiveCell.Value = "=discretesim(1,0,,,,,0.05,0.95,,,,)"
            ActiveCell.Offset(1, 0).Select
        Else
            ActiveCell.Value = "=discretesim(1,0,,,,,0.2,0.8,,,,)"
            ActiveCell.Offset(1, 0).Select
        End If
Loop
    Range("I4").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
```

```
            :=False, Transpose:=False
        Application.CutCopyMode = False
        ActiveWorkbook.Save

        Range("Z4").Select
        Range(Selection, Selection.End(xlDown)).Select
        Selection.Copy
        ActiveCell.Offset(0, i).Range("A1").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
        Application.CutCopyMode = False
Next i

' Update the Integration Effort for Process-Driven Factors
    ActiveWorkbook.Save
    Sheets("ClusterAnalysis").Select
    Range("S6").Select

'FIRST CLUSTER
    If IsEmpty(ActiveCell) Then

    Range("S11").Select
    Else
        Sheets("MonteCarloII").Select
        Range("U4").Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T6").Value)
        ActiveCell.Offset(1, 0).Select
```

```
    Loop
      ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S6").Value)
      ActiveCell.Offset(1, 0).Select
    Loop
      ActiveCell.Offset(0, -1).Select


      ActiveCell.Offset(0, 10).Range("A1:B1").Select
      Selection.Copy
      Sheets("Sheet1").Select
      Range("H3").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
      Sheets("ClusterAnalysis").Select
      Range("S11").Select
    End If


'SECOND CLUSTER
    If IsEmpty(ActiveCell) Then

    Range("S16").Select
    Else
      Sheets("MonteCarloII").Select
      Range("U7").Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X11").Value)
      ActiveCell.Offset(1, 0).Select
    Loop
      ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W11").Value)
      ActiveCell.Offset(1, 0).Select
    Loop
      ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V11").Value)
      ActiveCell.Offset(1, 0).Select
    Loop
      ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U11").Value)
      ActiveCell.Offset(1, 0).Select
    Loop
      ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("H10").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S16").Select
End If

'THIRD CLUSTER
If IsEmpty(ActiveCell) Then

Range("S21").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("H17").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S21").Select
End If

'FOURTH CLUSTER
   If IsEmpty(ActiveCell) Then

Range("S26").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
```

```
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("H24").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S26").Select
End If

'FIFTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("S31").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U26").Value)
```

```
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("H31").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S31").Select
End If

'SIXTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("S36").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("H38").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S36").Select
 End If

'SEVENTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("S41").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V36").Value)
   ActiveCell.Offset(1, 0).Select
```

```
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Sheet1").Select
   Range("H45").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S41").Select
End If

'EIGHTH CLUSTER

If IsEmpty(ActiveCell) Then
   Sheets("Sheet1").Select
   Range("A1").Select
Else
   Sheets("MonteCarlo").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select
```

```
   Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V41").Value)
      ActiveCell.Offset(1, 0).Select
   Loop
      ActiveCell.Offset(0, -1).Select

   Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U41").Value)
      ActiveCell.Offset(1, 0).Select
   Loop
      ActiveCell.Offset(0, -1).Select

   Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T41").Value)
      ActiveCell.Offset(1, 0).Select
   Loop
      ActiveCell.Offset(0, -1).Select

   Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S41").Value)
      ActiveCell.Offset(1, 0).Select
   Loop
      ActiveCell.Offset(0, -1).Select


      ActiveCell.Offset(0, 10).Range("A1:B1").Select
      Selection.Copy
      Sheets("Sheet1").Select
      Range("H52").Select
         Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
         :=False, Transpose:=False
      Sheets("Sheet1").Select
      Range("A1").Select
   End If

   Sheets("MonteCarlo").Visible = False
   Sheets("MonteCarloII").Visible = False

End Sub
```

Results

```
Sub Results()
' Updating the results for Results to show results
   Sheets("MonteCarlo").Visible = True
   Sheets("MonteCarloII").Visible = True
   ActiveWorkbook.Save
   Sheets("ClusterAnalysis").Select
   Range("L6").Select

'FIRST CLUSTER
   If IsEmpty(ActiveCell) Then
```

```
Range("L11").Select
Else
    Sheets("MonteCarlo").Select
    Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L6").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, 10).Range("A1:B1").Select
    Selection.Copy
    Sheets("Results").Select
    Range("D3").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Sheets("ClusterAnalysis").Select
    Range("L11").Select
End If
```

```
'SECOND CLUSTER
  If IsEmpty(ActiveCell) Then

  Range("L16").Select
  Else
    Sheets("MonteCarlo").Select
    Range("V4").Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, 10).Range("A1:B1").Select
    Selection.Copy
    Sheets("Results").Select
    Range("D10").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
```

```
        :=False, Transpose:=False
    Sheets("ClusterAnalysis").Select
    Range("L16").Select
End If

'THIRD CLUSTER
If IsEmpty(ActiveCell) Then

Range("L21").Select
Else
    Sheets("MonteCarlo").Select
    Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L16").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, 10).Range("A1:B1").Select
    Selection.Copy
```

```
    Sheets("Results").Select
    Range("D17").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Sheets("ClusterAnalysis").Select
    Range("L21").Select
End If

'FOURTH CLUSTER
    If IsEmpty(ActiveCell) Then

Range("L26").Select
Else
    Sheets("MonteCarlo").Select
    Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M21").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L21").Value)
    ActiveCell.Offset(1, 0).Select
```

```
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("D24").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L26").Select
End If

'FIFTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("L31").Select
Else
   Sheets("MonteCarlo").Select
   Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
```

```
  ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L26").Value)
  ActiveCell.Offset(1, 0).Select
Loop
  ActiveCell.Offset(0, 10).Range("A1:B1").Select
  Selection.Copy
  Sheets("Results").Select
  Range("D31").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
  Sheets("ClusterAnalysis").Select
  Range("L31").Select
End If

'SIXTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("L36").Select
Else
  Sheets("MonteCarlo").Select
  Range("V4").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q31").Value)
  ActiveCell.Offset(1, 0).Select
Loop
  ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R31").Value)
  ActiveCell.Offset(1, 0).Select
Loop
  ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P31").Value)
  ActiveCell.Offset(1, 0).Select
Loop
  ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O31").Value)
  ActiveCell.Offset(1, 0).Select
Loop
  ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N31").Value)
  ActiveCell.Offset(1, 0).Select
Loop
  ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("D38").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L36").Select
 End If

'SEVENTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("L41").Select
Else
   Sheets("MonteCarlo").Select
   Range("V7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L36").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("D45").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("L41").Select
End If

'EIGHTH CLUSTER

If IsEmpty(ActiveCell) Then
   Sheets("Results").Select
   Range("A1").Select
Else
   Sheets("MonteCarlo").Select
   Range("V7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("Q41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("R41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("P41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("O41").Value)
```

```
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("N41").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("M41").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("L41").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, 10).Range("A1:B1").Select
        Selection.Copy
        Sheets("Results").Select
        Range("D52").Select
            Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Sheets("Results").Select
        Range("A1").Select
    End If

' Update the Integration Effort for Process-Driven Factors
    ActiveWorkbook.Save
    Sheets("ClusterAnalysis").Select
    Range("S6").Select

'FIRST CLUSTER
    If IsEmpty(ActiveCell) Then

    Range("S11").Select
    Else
        Sheets("MonteCarloII").Select
        Range("U4").Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
        ActiveCell.Offset(0, -1).Select

    Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W6").Value)
        ActiveCell.Offset(1, 0).Select
    Loop
```

```
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V6").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U6").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T6").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S6").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select


    ActiveCell.Offset(0, 10).Range("A1:B1").Select
    Selection.Copy
    Sheets("Results").Select
    Range("H3").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
    Sheets("ClusterAnalysis").Select
    Range("S11").Select
  End If


'SECOND CLUSTER
  If IsEmpty(ActiveCell) Then

  Range("S16").Select
  Else
    Sheets("MonteCarloII").Select
    Range("U7").Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X11").Value)
    ActiveCell.Offset(1, 0).Select
  Loop
    ActiveCell.Offset(0, -1).Select

  Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W11").Value)
```

```
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S11").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("H10").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S16").Select
End If

'THIRD CLUSTER
If IsEmpty(ActiveCell) Then

Range("S21").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S16").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("H17").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S21").Select
End If

'FOURTH CLUSTER
   If IsEmpty(ActiveCell) Then

Range("S26").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S21").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("H24").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S26").Select
End If

'FIFTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("S31").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X26").Value)
   ActiveCell.Offset(1, 0).Select
```

```
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S26").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("H31").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S31").Select
End If

'SIXTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("S36").Select
Else
   Sheets("MonteCarloII").Select
   Range("U7").Select
```

```
Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S31").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("H38").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("ClusterAnalysis").Select
   Range("S36").Select
 End If

'SEVENTH CLUSTER

If IsEmpty(ActiveCell) Then

Range("S41").Select
Else
   Sheets("MonteCarloII").Select
```

```
    Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X36").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W36").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V36").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U36").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T36").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S36").Value)
    ActiveCell.Offset(1, 0).Select
Loop
    ActiveCell.Offset(0, -1).Select


    ActiveCell.Offset(0, 10).Range("A1:B1").Select
    Selection.Copy
    Sheets("Results").Select
    Range("H45").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Sheets("ClusterAnalysis").Select
    Range("S41").Select
End If

'EIGHTH CLUSTER

If IsEmpty(ActiveCell) Then
    Sheets("Results").Select
    Range("A1").Select
```

```
Else
   Sheets("MonteCarlo").Select
   Range("U7").Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("X41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("W41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("V41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("U41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("T41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select

Do Until (ActiveCell.Value = Worksheets("ClusterAnalysis").Range("S41").Value)
   ActiveCell.Offset(1, 0).Select
Loop
   ActiveCell.Offset(0, -1).Select


   ActiveCell.Offset(0, 10).Range("A1:B1").Select
   Selection.Copy
   Sheets("Results").Select
   Range("H52").Select
      Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Sheets("Results").Select
   Range("A1").Select
End If

Sheets("MonteCarlo").Visible = False
Sheets("MonteCarloII").Visible = False
ActiveWorkbook.Save
```

End Sub

Sequencing

```
Sub Sequencing()
'   ActiveWorkbook.Save
  Sheets("ClusterRepresentation").Select
  Range("J3").Select
Do Until IsEmpty(ActiveCell)
   If (ActiveCell.Value < ActiveCell.Offset(-1, 0).Value) Then
      If (ActiveCell.Offset(-1, 1) <> "Sequencing") Then
      response = MsgBox("Do you want to combine this function with the previous clustered function [same cluster]?", vbYesNo + vbQuestion, "Combination Possible")
         If response = vbYes Then
            ActiveCell.Offset(0, 1).Value = "Keep"
         Else
            Do Until ActiveCell.Value <> ActiveCell.Offset(1, 0).Value
            ActiveCell.Value = Range("M2").Value + 1
            ActiveCell.Offset(0, 1).Value = "Sequencing"
            ActiveCell.Offset(1, 0).Select
            Loop
            ActiveCell.Value = Range("R2").Value + 1
            ActiveCell.Offset(0, 1).Value = "Sequencing"
         End If
      End If
   End If
   ActiveCell.Offset(1, 0).Select
Loop
   Range("P2").Select
   ActiveWorkbook.Save
   'Update Cluster Analysis Sheet
   Range("O1:V42").Copy
   Sheets("ClusterAnalysis").Select
   Range("B4:B10").Select
   ActiveSheet.Paste
   Application.CutCopyMode = False
   MsgBox ("Now rate the factor from the dropdown menu starting under the heading 'Benefit Factors'")
End Sub
```

Setup Clustering

```
Public Sub SetupClustering()
'Delete Table Rows
   Sheets("ClusteringI").Select
   Range("A5:K5").Select
   Range(Selection, Selection.End(xlDown)).Select
```

```
    For i = 1 To Range("ProcessTable").Rows.Count - 3
    Selection.ListObject.ListRows(3).Delete
    Next i
 'Cluster2 Delete Table Rows
    Range("N5:V5").Select
    Range(Selection, Selection.End(xlDown)).Select
    For i = 1 To Range("ProcessTable2").Rows.Count - 3
    Selection.ListObject.ListRows(3).Delete
    Next i
  'Cluster3 Delete Table Rows
    Range("AB5:AJ5").Select
    Range(Selection, Selection.End(xlDown)).Select
    For i = 1 To Range("ProcessTable3").Rows.Count - 3
    Selection.ListObject.ListRows(3).Delete
    Next i
   'Cluster4 Delete Table Rows
    Range("AQ5:AY5").Select
    Range(Selection, Selection.End(xlDown)).Select
    For i = 1 To Range("ProcessTable4").Rows.Count - 3
    Selection.ListObject.ListRows(3).Delete
    Next i
   'Cluster5 Delete Table Rows
    Range("BG5:BO5").Select
    Range(Selection, Selection.End(xlDown)).Select
    For i = 1 To Range("ProcessTable5").Rows.Count - 3
    Selection.ListObject.ListRows(3).Delete
    Next i


'Copy Names for calculation from HTA sheet
    Sheets("HTA").Select
    Worksheets("HTA").Range("A10").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.Copy
'Copy in first cluster
    Sheets("Clustering").Select
    Range("A3").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    Range("A3").Select
'Copy in second cluster
    ActiveCell.Offset(0, 13).Range("A1").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
'Copy in third cluster
    ActiveCell.Offset(0, 14).Range("A1").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
```

```
'Copy in fourth cluster
   ActiveCell.Offset(0, 15).Range("A1").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
'Copy in fifth cluster
   ActiveCell.Offset(0, 16).Range("A1").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
' Exit copy mode
   Application.CutCopyMode = False
'End Sub

'Copy Data for calculation from HTA sheet
   Sheets("HTA").Select
   Worksheets("HTA").Range("C10").Select
   ActiveCell.Range("A1:H1").Select
   Range(Selection, Selection.End(xlDown)).Select
   Selection.Copy
'Copy in first cluster
   Sheets("Clustering").Select
   Range("B3").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
   Range("B3").Select
'Copy in second cluster
   ActiveCell.Offset(0, 13).Range("A1").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
'Copy in third cluster
   ActiveCell.Offset(0, 14).Range("A1").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
'Copy in fourth cluster
   ActiveCell.Offset(0, 15).Range("A1").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
'Copy in fifth cluster
   ActiveCell.Offset(0, 16).Range("A1").Select
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
      :=False, Transpose:=False
' Exit copy mode
   Application.CutCopyMode = False
'End Sub

'FILL EMPTY CELLS ZERO
   Range("B3").Select
   ActiveCell.Range("A1:H1").Select
   Range(Selection, Selection.End(xlDown)).Select
```

```
Selection.SpecialCells(xlCellTypeBlanks).Select
' Fill_Empty_Cells_Zero Macro
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
   SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
   ReplaceFormat:=False
'Format Cluster2
Range("O3").Select
ActiveCell.Range("A1:H1").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.SpecialCells(xlCellTypeBlanks).Select
' Fill_Empty_Cells_Zero Macro
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
   SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
   ReplaceFormat:=False
'Format Cluster3
Range("AC3").Select
ActiveCell.Range("A1:H1").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.SpecialCells(xlCellTypeBlanks).Select
' Fill_Empty_Cells_Zero Macro
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
   SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
   ReplaceFormat:=False
'Format Cluster4
Range("AR3").Select
ActiveCell.Range("A1:H1").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.SpecialCells(xlCellTypeBlanks).Select
' Fill_Empty_Cells_Zero Macro
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
   SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
   ReplaceFormat:=False
'Format Cluster5
Range("BH3").Select
ActiveCell.Range("A1:H1").Select
Range(Selection, Selection.End(xlDown)).Select
Selection.SpecialCells(xlCellTypeBlanks).Select
' Fill_Empty_Cells_Zero Macro
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
   SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
   ReplaceFormat:=False
```

```
'Formatting the clusters
    Range("A3").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Style = "Normal"
Range("N3").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Style = "Normal"

Range("AB3").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
Selection.Borders(xlEdgeLeft).LineStyle = xlNone
Selection.Borders(xlEdgeTop).LineStyle = xlNone
Selection.Borders(xlEdgeBottom).LineStyle = xlNone
Selection.Borders(xlEdgeRight).LineStyle = xlNone
Selection.Borders(xlInsideVertical).LineStyle = xlNone
Selection.Borders(xlInsideHorizontal).LineStyle = xlNone
Range("AQ3").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Style = "Normal"

Range("BG3").Select
Range(Selection, Selection.End(xlToRight)).Select
Range(Selection, Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyle = xlNone
Selection.Borders(xlDiagonalUp).LineStyle = xlNone
Selection.Borders(xlEdgeLeft).LineStyle = xlNone
Selection.Borders(xlEdgeTop).LineStyle = xlNone
Selection.Borders(xlEdgeBottom).LineStyle = xlNone
Selection.Borders(xlEdgeRight).LineStyle = xlNone
Selection.Borders(xlInsideVertical).LineStyle = xlNone
Selection.Borders(xlInsideHorizontal).LineStyle = xlNone
Range("BY3").Select

' Clear_And_Fill_Centroids Macro
Range("Centroids[[C_Field1]:[C_Field8]]").Select
Application.CutCopyMode = False
Selection.ClearContents
Selection.SpecialCells(xlCellTypeBlanks).Select
Selection.Replace What:="", Replacement:="0", LookAt:=xlPart, _
    SearchOrder:=xlByRows, MatchCase:=False, SearchFormat:=False, _
    ReplaceFormat:=False
Range("BY3").Select
```

```
    ActiveCell.FormulaR1C1 = "1"
    Range("BZ4").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("CA5").Select
    ActiveCell.FormulaR1C1 = "1"
    Range("CB6").Select
    ActiveCell.FormulaR1C1 = "1"

    Range("Centroids").Select
    Selection.NumberFormat = "0"

    MsgBox ("Please click on the Clustering Sheet for further instructions.")

End Sub
Sub Update_Centroids()
'
' Update_Centroids Macro
'

'
    Range("AA5:AH8").Select
    Selection.Copy
    Range("Centroids[[C_Field1]:[C_Field8]]").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
End Sub
```