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Manuscript title: Modularisation and offsite in engineering construction: an early decision-support tool

Authors: Chris Goodier[1*], Alistair Gibb[2], Mauro Mancini[3], Christoph Turck[4], Osman Gjepali[5], Edwin Daniels[6]

Affiliation: [1]School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK, ORCID: https://orcid.org/0000-0001-6464-4065; [2]School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK, https://orcid.org/0000-0002-3660-010X; [3]Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy; [4]Chief Data Office, Lloyds Banking Group, London, UK; [5]Submarine & HV Energy Projects, Prysmian Group, Milano, Italy; [6]Construction Manager, Fluor, Amsterdam, Netherlands

***Corresponding author:** Chris Goodier, School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK

E-mail: c.i.goodier@lboro.ac.uk

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Abstract

Modularisation and offsite manufacture are increasing in the engineering construction sector. Decision-support tools for determining a project's suitability for offsite modular construction are currently limited or outdated, leading to decisions being based mainly around capital cost, experience or intuition. This paper reports on the development of a robust, empirically-based decision-support tool for decision makers and clients. A mixed-method methodology was conducted involving engineering construction clients, contractors, consultants and suppliers from all over Europe, after which the tool was developed, piloted and validated with practicing engineers. It is the first globally-applicable tool enabling informed and auditable decisions on using an offsite modular approach for project delivery.

Keywords: Information technology; Infrastructure planning; Management; Planning & scheduling; Project management

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1. Introduction

Construction decisions are influenced by many stakeholders including clients, designers, contractors, suppliers and funding bodies, such that making decisions can be a long and complex process (Newcombe, 2003; Bakht and El-Diraby 2015; Chinyio and Olomolaiye, 2010). Additionally, early decisions concerning a project are often made without full knowledge of all options and without direct involvement of some of the relevant parties (Fellows and Liu, 2012). This can result in failure to consider more suitable options, leading to delay, extra cost and decreased quality (Doloi, 2013; Fellows and Liu, 2012).

The problem is particularly acute in the engineering construction sector, where projects can vary greatly, be very expensive and highly complex (Mancini, 2014; Brookes, 2012). According to the UK Engineering Construction Industry Association (2019), about 50,000 workers in Britain are employed by the engineering construction sector, directly contributing 2% of the national gross domestic product. With a total economic output of £117 billion in 2017 (Rhodes, 2018), the UK construction industry, and the engineering construction sector as part of it, can be considered of significant importance to the national economy.

Since the reports by Egan (1998) and Latham (1994), it has been argued that UK construction had, and still has, many areas in which to improve to become more efficient, less fragmented and more transparent (Constructing Excellence, 2009; Farmer, 2016). The UK government has identified the use of offsite manufacturing in construction, among other ideas, as a way of addressing many of these challenges

(Department for Business, Innovation and Skills, 2012). In 2017 it announced a 'presumption in favour' of offsite by 2019 across suitable capital programmes, where it represents best value for money, for five government departments: Transport, Health, Education, Justice, and Defence.

Offsite involves the manufacture and pre-assembly of elements of the project in a factory environment before subsequent transportation and installation into the final location. Many researchers have identified offsite as a way to reduce inefficiencies and generate other positive effects (e.g. Goodier & Gibb, 2007; Goodier & Gibb, 2005; Ahmad *et al.*, 2019; Azhar *et al.*, 2013; Gibb and Isack, 2003; Blismas *et al.*, 2005). In principle, the term 'modularisation' means the same as offsite, but is more commonly used on projects of a larger scale with higher levels of pre-work. It is a general term used to encompass all levels of prefabrication, including modularisation and offsite (Gibb, 1999). Modularisation is of particular relevance to the engineering construction sector, with companies often working on large projects in remote locations or constrained sites (Figure 1) (Cigolini and Castellano, 2002).

A lack of existing metrics to assess the benefits of offsite has been identified in the past, with decisions based around capital cost, experience or intuition (Pan *et al.*, 2008). Until evaluation is more holistic and value-based rather than cost-based, uptake of offsite is expected to remain slow (Blismas *et al.*, 2006; Farmer, 2016; House of Lords, 2018). However, significant progress has recently been made (Mao *et al.*, 2016; House of Lords, 2018; McCarney *et al.*, 2019; Ahmad *et al.*, 2019). UK construction research body Ciria (2019), for example, has an ongoing project on quantifying the benefits of offsite construction, including modular, and the UK standards company BSI recently reviewed current and future standards for offsite construction and modularisation (Price *et al.*, 2019).

Much research has been focused on the applications of offsite in smaller-scale projects, predominately housing, and its advantages, disadvantages, drivers and constraints (e.g. O'Connor *et al.*, 2014; Azhar *et al.*, 2012; Blismas *et al.*, 2005; Pan *et al.*, 2008). However, since the seminal work of Tatum *et al.,* (1987), research into modularisation on large engineering construction projects has been limited. Past tools were either developed many years ago (Murtaza and Fisher, 1994; Cigolini and Castellano, 2002; Haas and Fagerlund, 2002) or are not ideally suited for use in the engineering construction sector (Soetanto *et al.*, 2004; Blismas *et al.*, 2005; Luo *et al.*, 2006; Pan *et al.*, 2008; Chen *et al.*, 2010). The decision process and subsequent provision of a framework for structured decision making in engineering construction therefore remains an area of under-researched interest.

2. Engineering construction and modularisation

The engineering construction sector includes the design and delivery of industrial plant and involves large-scale construction in oil and gas, power generation, processing and manufacturing, and water and environmental works (Brookes, 2012; Vernikos *et al.* 2013b). Outside of engineering construction, offsite has many different names and terms, including offsite production, offsite fabrication, offsite manufacturing, offsite construction, preassembly, prefabrication, standardisation, industrialised building system or just offsite. Modular and modularisation are also used, and these are used in this paper. Modularisation refers to the highest levels of pre-work. The term pre-work is used to describe all levels of prefabrication and includes modularisation.

Ciria (1997) describes pre-work as the, 'extensive use of processes and components with regularity and repetition', whereas Fredriksson (2006) describes it in more detail as, 'the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks'.

Even though there are slight variances in the understanding of the term modularisation, most literature agrees on the main aspect of a module being fabricated in location A and subsequently being transported to its final location B. The term module itself is defined as, 'a product resulting from a series of remote assembly operations. It is usually the largest trans-portable unit or component of a facility. A module consists of a volume fitted with all structural elements, finishes, and process components which, regardless of system, function or installing craft, are designed to occupy that space. Modules may contain prefabricated components or preassemblies and are frequently constructed away from the jobsite', (Tatum *et al.*, 1987). Examples of modules are shown in Figures 2 and 3.

In the twentieth century, modularisation has been increasingly employed by the construction industry. The offshore sector was an important stimulus for increased modularisation due to the remoteness of installation and has influenced contemporary ideas and approaches on modularisation (as opposed to offsite buildings onshore) (Cigolini and Castellano, 2002; Gibb, 1999).

Modularisation is increasingly being used globally predominately in the building and public sectors (Lawson *et al.*, 2014; Arif and Goulding, 2013). Examples include student residences, private and social housing, hotels, military accommodation, health sector buildings, educational buildings, prisons, plant rooms and bathrooms (Lawson *et al.*, 2014). It is also being used in engineering construction (Figure 4). Civil engineering projects have always used offsite approaches, for example precast concrete bridge beams and tunnel linings, though less so modularisation (Vernikos *et al.*, 2012).

3. Benefits and drawbacks of modularisation

Modularisation is best evaluated as early as possible in the project (Ciria, 2019; McCarney *et al.,* 2019; Vernikos *et al.* 2013a; Emes, 1992; Ciria, 1997; Gibb and Isack, 2003; Javanifard *et al.*, 2013). Gibb (1999) explains that, ‘to maximise the benefits from offsite…it is essential that a project wide strategy is developed at an early stage in the project’.

Emes (1992) states that the offsite strategy must be evaluated from an ‘overall project view’ rather than an ‘element view’. Moreover, benefits deriving from offsite depend on the project specifications, circumstances and combination of construction techniques employed. One cannot simply list them and be sure of their realisation in every project (Blismas *et al.* 2006).

The main benefits of modularisation identified by previous research are summarised in Table 1, and drawbacks are summarised in Table 2.

4. Decision-support tools

Decision-support tools are common in the finance and management sector, with computerised solutions providing managers with interactive financial and managerial planning systems and purchase advice (Aziz, 2003; Melouk *et al.*, 2013). Decision-support tools are also used in healthcare to guide medical practitioners regarding when to advise certain treatments or issue recommendations (Tisnado *et al.*, 2015). Possible media for decision-support tools include paper, software or web-based applications, and outputs are typically based on a logical or numerical system using multi-criteria decision analysis involving, 'a finite or infinite set of alternatives, at least two criteria, and, obviously, at least one decision-maker', (Figueira *et al.* 2005).

Within multi-criteria decision analysis there are many different approaches to describe relationships between different criteria and create scoring systems to find the most suitable option mathematically or logically (Jato-Espino *et al.*, 2014). A small number of decision-support tools exist in construction, but are either out of date, and/or do not cover engineering construction. Modex was the earliest identifiable tool related to modularisation, developed by the Construction Industry Institute in Texas, USA (Haas and Fagerlund, 2002). Autmod3 was a planning tool for modular building systems (Padron *et al*, 2007), though not intended for the very early stage of the decision-making process, but more so the implementation of modularisation. Pan *et* *al.,* (2008) also developed a decision-support matrix for build system selection in housing construction.

5. Methodology

Information was gathered using various means from engineering construction clients, contractors, consultants and suppliers from all over Europe between 2014 and 2016. This included a survey via the European Construction Institute (ECI), semi-structured interviews, a Delphi-style questionnaire, and several industry workshops.

Sampling was influenced by the availability of ECI members, therefore providing a non-random, single-stage sample. The ECI is a pan-European network of focussed on delivering construction and engineering excellence through the sharing of knowledge and application of best practice. It has regional centres in the UK, Italy and Benelux (http://www.eci-online.org/).

Workshop participants were recorded and the data transcribed, and thematically analysed in a continuous process with multiple rounds (Davidson, 2009). The work was conducted in two consecutive phases (Figure 5).

5.1 Phase 1

Phase 1 focused on four main techniques of data collection via an explanatory sequential mixed method approach (Table 3). A web-based questionnaire survey of ECI engineering construction professionals (n=18), distributed via email, refined and validated findings from a literature review. Key questions involved benefits/drawbacks of modularisation, and factors influencing decisions regarding modularisation. Semi-structured phone interviews (30−75 minutes) with questionnaire respondents helped refine responses (n=12). Open-ended questioning and respondent anonymity helped encourage real examples and personal experiences.

Findings were consolidated and further refined via a Delphi approach by means of a paper-based plenary questionnaire (n=46) and a workshop of individual focus groups (n=28) at the ECI's international conference in Amsterdam in June 2015. The questionnaire was used to identify the ten most critical factors to consider when evaluating the adoption of modularisation in engineering construction projects, the workshop experts then narrowed this to six, and fed back on the significance and novelty of each.

5.2 Phase 2

Phase 2 focused on three main techniques of data collection through a convergent parallel mixed method approach (Table 4).

An additional literature review investigated decision-support tools specifically − potential media and platforms, structure and functionality (e.g. Mao *et al.*, 2016; Zakaria *et al.*, 2016; Li *et al.*, 2016). Workshop 2 was then held with ECI engineering construction industry experts in October 2015 (n=12). Phase 1 findings, including drivers, constraints were discussed, as were decision-support tools, and a concept design of a possible modularisation decision-support tool.

An online questionnaire, based on phase 1 research findings, workshop 2 and literature, was then distributed to the ECI modularisation task force (n=10), using open-ended questions to allow participants to feedback regarding the presented decision-support concept design and content.

Data from workshop 2 and the questionnaire were then used to further develop the decision-support tool, which was presented to several smaller focus groups to trial and evaluate in workshop 3, in Farnborough, UK in March 2016 (n=25).

6. Analysis and discussion

6.1 Phase 1

In phase 1, 46 drivers and 41 constraints were identified and sorted into four categories: client objectives (Table 5), site characteristics (Table 6), project execution and management approach (Table 7), and engineer procure construct, contractor and industry player status (Table 8). Through these drivers and constraints, the likelihood of benefits and capacity to implement a modular approach can be assessed for a typical project. The list of drivers and constraints is not exhaustive, with only the most relevant factors included (Tables 5−8); their potential impact are designated high (H), medium (M) or low (L).

An initial concept design, which was eventually developed into the European Construction Institute Modularisation (Ecimod) decision-support tool, was created based on phase 1 (Figure 6).

The concept design comprised of three levels: initial selection, applicability and feasibility. The first level included the option to select specific industries or module sizes. The second level (applicability) included eight categories with assorted drivers and constraints from Table 5. It considered the likelihood of gaining benefits from adopting modularisation. The third level (feasibility) included six categories with assorted drivers and constraints from Tables 6−8. It considered the capacity of a project to adopt modularisation.

The impacts of each driver and constraint were assigned a fixed numerical value in form of the staple scale seen in Table 9. User inputs were provided through the selection of one of the terms shown in the unidirectional Likert scale in Table 10. These were also assigned numerical values.

Drivers and constraints with their assigned fixed impact were to be provided to the user with possible input in form of the choices seen in Table 10. Both the fixed and the selected numerical values were then multiplied to give a score. During the second level (applicability), scores were also weighted by means of a percentage importance given to each of the eight categories.

The score of the second level was to be used to advise the user on the likelihood of modularisation generating benefits based on a set range of values (Table 11). The scores of the third level were to be used to display specific drivers and constraints to the user based on their relevance to the project (Table 12).

The rating system proposed for this system applied the ‘simple multi-attribute rating technique’ (Smart), as used by other tools (Haas and Fagerlund, 2002; Chen *et al.*, 2010). This linear additive technique was chosen for its simplicity and ease of use, while providing a sufficient measure of sophistication (Jato-Espino *et al.*, 2014). Advantages include unity, applicability, interdependence, operations and relevancy, but disadvantages can include complexity, accuracy, sensitivity and consistency (Patel *et al*, 2017).

6.2 Phase 2

In phase 2, workshop 2 and the questionnaire revealed that participants, irrespective of industry and experience, agreed that a website and an Excel-based tool were the most appropriate solution to implement a decision-support tool, with an app-based decision-support tool popular amongst the young, and paper and 'other' the least popular.

Questionnaire and workshop 2 responses were used to construct matrices for all categories and associated drivers and constraints (Table 13 and Figure 7). Questions asked included

- Q1. Are there any drivers/constraints missing from this element?
- Q2. Is the weighting (H-M-L) of each driver/constraint appropriate?
- Q3. Is the wording of each driver/constraint easily understandable?

Attendees were also asked to write down suggested amendments and improvements if they thought suitable.

For each column, a percentage disagreement was calculated, based on the number of times that a participant was not satisfied with a particular question. These values were used to identify specific aspects of factors for which more than 30% of participants disagreed, as well as highlighting potential candidates for follow-up interviews. For each row, a percentage disagreement was calculated, based on the total number of questions the participants answered compared to the number of times that participants were not satisfied.

A total of 246 questions were answered for the applicability level and 186 for the feasibility. 70 and 47 of these were answered with disagreement, giving an overall disagreement with the factors and questions of 22% and 20% respectively. These are broken down further into the disagreement for specific questions for each table (Tables 10 and 11).

As complete satisfaction is difficult to achieve, except for factors overly obvious or predictable, a disagreement of 22% and below was considered acceptable. In 90% of cases, participants wanted to include a specific, single driver or constraint only, or to change its impact, resulting in the significant difference between Q1 and Q2 or Q3 for both tables. This related to the variety and complexity of differing projects and locations, subjected to different boundary conditions, as described by Brookes (2012). This agrees with a participant pointing out that, ‘proposed drivers/weighting can be correct for a typical project, although it has to be noticed that each project is unique, so drivers and corresponding weighting are specific for each project/situation’, (engineer−procure−construct person with 20 years’ experience).

As a result of the percentage disagreement for Q1 and the above feedback, a single user-specified driver and constraint were added to each factor along with the option to change the impacts of the drivers and constraints to allow a degree of adaptation. This option was paired with an embedded warning that consistency and reliability of the tool’s output would decrease with changing impacts.

7. Recommendations

Based on responses inputted into the tool, a final recommendation was produced. The questionnaire confirmed that the second-level (applicability) recommendations were acceptable for most participants, with some final amendments made regarding wording and use of percentages. Figure 8 is an example extract of the final decision-support tool recommendation page.

The feasibility recommendations were presented at workshop 3 for feedback and refinement, which included requests for a simple list of the relevant drivers and constraints, further guidance for each, a printable final output report.

8. Software development

Following workshop 3, the decision-support tool was created using Microsoft Excel and basic programming in Visual Basic for Applications. A single workbook containing a multitude of worksheets through which the user navigates was applied.

All relevant data from phase 1 and 2 was transferred to multiple Excel worksheets, containing all data from the concept design as well as appropriate welcome and explanation screens, linked via formulas. Functionality was provided via comment boxes and drop-down menus from which the user could select (in order to restrict user inputs). A welcome screen, navigational command buttons and a main menu through which different parts could be accessed instantaneously were also implemented, as was a tool user guide. An example of a navigable page requiring user input is shown in Figure 9.

9. Conclusions

Offsite and modular construction is increasing in engineering construction, and current decision-support tools are currently limited or outdated. A robust empirically-based decision-support tool for decision makers and clients, to be used at the conceptual stage has therefore been developed, piloted and validated using a mixed method methodology incorporating an online survey, semi-structured interviews, a Delphi-style questionnaire, and three industry workshops with experienced engineering construction practitioners.

Phase 1 provided the fundamental knowledge regarding the key drivers and constraints and the development and population of the database from which to build the tool. Phase 2 validated and refined phase 1, leading to the creation of the decision-support tool. Limitations to the work and the tool would always exist due to the finite number of respondents involved in the data collection. Useful additional further work would be the trialling of case study data within the tool, together with follow-up interviews to help validate the data.

This is the first time that a globally-applicable tool for modularisation based on empirical data has been presented, enabling informed and auditable strategic decisions to be made regarding the potential success of modular construction approaches in specific contexts.

Further validation and refinement of the tool through the observation of real-life projects would be beneficial, which would help crystallise the wording of the drivers, constraints and recommendations, as well as validate the underlying mathematical relationships. Updates on the embedded drivers and constraints will also be needed in the future to adjust for new developments in the engineering construction, modularisation, and other related sectors.

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Table 1. Benefits of modularisation

	Mancini, 2014	O'Connor *et al.*, 2014	Javanifard *et al.*, 2013	Ukces, 2013	Vernikos *et al.*, 2014	McGraw Hill Construction, 2011	Smith, 2011	Modular Building Institute, 2010	Bowden *et al.*, 2006	Blismas *et al.*, 2006	Gibb and Isack, 2003	Haas and Fagerlund, 2002	Ciria, 1997	Gibb, 1999
Shorter schedule	✔	✔	✔		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Higher quality	✔	✔		✔	✔		✔		✔	✔	✔	✔		✔
Reduction of cost		✔	✔	✔		✔				✔	✔	✔	✔	✔
Enhanced sustainability		✔	✔										✔	
Improved health and safety	✔		✔			✔	✔		✔	✔		✔	✔	✔
Improved predictability and reliability		✔	✔	✔				✔	✔				✔	✔
Higher workers' productivity	✔	✔	✔			✔	✔		✔	✔	✔		✔	✔
Possibility of reusing and relocating project														✔
Easier testing and maintenance									✔				✔	
Project risk reduction							✔							
Optimisation of onsite preliminaries								✔						
Opportunities for innovation, project options and customer choices													✔	
Waste reduction			✔			✔			✔					

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Table 2. Drawbacks of modularisation

	Mancini, 2014	Vernikos *et al.*, 2014	O'Connor *et al.*, 2014	Ukces, 2013	McGraw Hill Construction, 2011	Gibb and Isack, 2003	Haas and Fagerlund, 2002	Ciria, 1997	Gibb, 1999
Increased engineering/design effort	✔		✔			✔	✔	✔	✔
Decreased flexibility			✔			✔	✔		
Increased project cost	✔		✔			✔			
Lack of experience		✔	✔	✔	✔				
Negative connotation of the method				✔					
More coordination required		✔	✔				✔		
Increased logistics difficulties		✔	✔				✔		✔
Operational issues						✔	✔		
Transportation difficulties	✔		✔		✔		✔	✔	✔
Time lag of new technologies				✔					

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Table 3. Phase 1 research methods

Method	Details
Web-based questionnaire	Issued 33, responses 18 (55%)
	Role: 31% engineer procure construct, 28% contractor, 17% client/owner, 12% consultant, 12% supplier
Semi-structured phone interviews	Invited 18, accepted 12 (67%)
	Role: 35% engineer procure construct, 23% contractor, 23% client/owner, 8% consultant, 8% supplier
Plenary workshop questionnaire	Issued 70, responses 46 (66%)
Workshop 1 with focus groups (60 minutes)	Attendees 28, focus group size 5−6

Table 4. Phase 2 research methods

Methods	Details
Workshop 2 (60 minutes)	Attendees 12
	Industry: 35% power/energy, 24% transport/logistics, 29% oil/gas, 12% education
	Experience: 25% 0−10 years, 33% 11−0 years, 25% 21−30 years, 17% 31−40 years
Questionnaire survey	Issued 18; responses 10 (56%)
	Role: 50% engineer procure construct, 20% contractor, 10% client/owner, 10% consultant, 10% supplier
	Industry: 29% power/energy, 29% oil/gas, 21% transport/logistics, 21% chemical
	Experience: 10% 0−10 years, 60% 11−20 years, 10% 21−30 years, 20% 31−40 years
Workshop 3 with focus groups (150 minutes)	Attendees 25, focus group size 4−6

Table 5. Client objectives

Category	**Drivers**	**Constraints**
Cost of the project	H: Lower onsite cost H: Lower labour cost per unit due to higher productivity offsite M: Higher financial benefits due to shorter schedule L: Less material and reworks reduction L: Lower onsite preliminaries cost L: Savings on external consultant for design L: Lower transportation cost of all the equipment onsite L: Lower testing cost	H: Higher engineering and design cost due to higher working hours required H: Transportation cost of the module M: Higher material supply cost, due to better offsite quality (if considering a direct comparison) M: Expenses to set the infrastructure for the transportation to the site (warranties, insurances, local taxes) L: Higher cost of the skilled workers, stably employed in the offsite facility L: Higher expenses on implementing sustainable equipment and processes
Running cost of the plant	M: Improved sustainability of plant process L: Higher quality can lead to less business stops L: Easier and faster maintenance procedure (less hinder for the existing business) L: Higher residual value at the end of the life of the process modules (reuse and refurbishment)	
Schedule time	H: Parallel working M: Diminished delays and work slowdown in the offsite facility M: Higher productivity in the offsite facility	L: More detailed engineering effort (considering also transportation and risk mitigation) L: Higher team organisation and coordination effort
Quality of the plant	M: More organised and optimised working footprint in the offsite facility M: Better trained workers	M: Location and poor organisation of the offsite facility can inhibit the drivers (cheap labour localities, recent opening)

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	M: Testing of the whole process equipment (not just parts of it but the entire piece) M: Better quality of the material due to probable long term relationship with suppliers	M: Second-hand material adoption
Certainty and predictability	H: Higher schedule predictability due to simultaneous work H: Higher certainty of offsite facility cost (e.g. labour cost, supply, transport) H: Early freeze of design and decisions H: Less hinders by external conditions (e.g. climatic)	M: Higher risk (e.g. during transportation and installation) M: Higher necessity of coordination between the project phases and individuals
Health and safety	H: Reduced risk and workers' exposure to onsite working conditions (dangerous activities, adverse climate) H: Higher trained workforce offsite H: Improved footprint, activities schedule and equipment organisation	
Sustainability	M: Less pollution (due to less vehicles movement on site) L: More environmentally friendly offsite working procedures L: Less material usage, energy and water consumption L: Less material waste L: Facilitate recycling	L: Higher pollution during the transport of modules
Develop local content		H: Government asks to employ local workers H: Government asks to use local suppliers and local companies

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Table 6. Site characteristics

Category	Drivers	Constraints
Site conditions	H: Restricted space for material storage (stock) H: Brownfield site, hinder living environment M: Not conductive working footprint onsite	H: Restrictions on usage and placement of cranes M: Reduced space for the movement of modules
Site location	H: Lack of skilled workforce onsite H: Too expensive onsite workforce M: Closeness to living accommodation of the construction site (necessity to reduce noise, dust, congestion of the site) M: Problematic political situation in the construction area	H: Long distance of the site from sea or rivers H: Adverse onsite climatic conditions H: Availability of skilled workforce at a fairly price in the construction site M: Closeness to big cities of the construction site (good infrastructural systems)
Transport infrastructure		H: Lack of transport infrastructure H: Heavy lift cranes not assured M: Permits and legal legislation barriers on module movements

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Table 7. Project execution and management approach

Category	Drivers	Constraints
Engineering and design	M: Possibility to introduce standardisation for project replication M: Early involvement of the client and key project players L: Early focus on design issues (resolution of infeasibilities)	H: Limited late changes due to early freeze of design and decisions M: High engineering and design effort, mainly detailed engineering, necessity to design for transportation and maturity of the information at the early stage
Complexity and risk	M: Opportunity for an early planning and mitigation of risks (e.g. during transportation) L: Few opportunities to introduce changes during the project, that reduces the cost and time scope changes.	H: High transportation risk (module damaged or lost) M: Increased engineering complexity L: Early procurement might lead to higher logistic complications L: Risk allocation shift (e.g. from engineering design to engineering construction)
Coordination and communication	L: Increased relationship with suppliers due to the increased contacts	M: Higher coordination and communication required during transportation and installation M: More effective communication and coordination required between project operators L: Higher requirements for suppliers

Table 8. engineer procure construct, contractor and industry players

Category	Drivers	Constraints
engineer−procure−construct propensity to go modular	H: Economic interests in advising a modular approach (e.g. design hours payment) H: Strong relationship with network of subcontractors	H: Economic interest in advising a stick build approach H: Interests in not advising a modular approach due to lack of knowledge and experience
Experience of the contractor		H: Lack of consolidate methods and management procedures in facing modular projects H: Lack of critical information management H: Lack of risk evaluation and mitigation (e.g. during transportation and installation) M: Lack of coordination and communication methods
Industry understanding of modularisation		H: Client's lack of understanding of pros and cons of modularisation H: Lack of project operator's knowledge about modularisation

Table 9. Numerical values associated with impacts

Driver impact			**Constraint impact**		
High	Medium	Low	High	Medium	Low
+9	+3	+1	-9	-3	-1

Table 10. User inputs

Unknown	**Not applicable**	**Somewhat applicable**	**Applicable**	**Very applicable**
0	0	1	2	3

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Table 11. Second level scores

Score range	Benefits from modularisation
Less than 0	Very unlikely
Between 0 and 10	Unlikely
Between 10 and 20	Likely
Between 20 and 30	Very likely
More than 30	Extremely likely

Table 12. Third-level scores

Score range	Relevance to project
More than 18	Strong driver
Between 6 and 18	Weak driver
Between -6 and -18	Weak constraint
Less than -18	Strong constraint

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Table 13. Extract of matrix used in analysis (✔ agreement, □ disagreement)

Participant	Total project cost			Operating costs of facility			Time schedule of the project			Participant disagreement
A	-	-	-	-	-	-	✔	✔	✔	0%
B	-	-	-	-	-	-	✔	✔	□	33%
C	-	-	-	-	-	-	□	✔	✔	33%
D	-	-	-	-	-	-	✔	✔	✔	0%
E	-	-	-	-	-	-	✔	□	✔	33%
F	-	-	-	-	-	-	✔	✔	✔	0%
G	-	-	-	-	-	-	□	✔	✔	33%
H	-	-	-	-	-	-	✔	✔	✔	0%
I	□	✔	□	□	✔	✔	-	-	-	33%
J	✔	✔	✔	✔	✔	✔	-	-	-	5%
K	✔	✔	□	□	□	✔	-	-	-	43%
L	□	✔	□	✔	□	✔	-	-	-	33%
M	□	✔	✔	✔	✔	✔	-	-	-	24%
N	□	□	□	□	□	□	-	-	-	100%
O	□	✔	✔	□	✔	✔	✔	✔	□	29%
P	✔	✔	✔	✔	✔	✔	□	✔	✔	4%
Q	✔	✔	✔	✔	✔	✔	□	✔	✔	4%
R	□	□	✔	✔	□	✔	□	✔	✔	25%
Question	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	
Factor disagreement	60%	20%	40%	30%	40%	10%	50%	10%	20%	

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Table 10. Disagreement with individual questions − applicability

Question	Disagreement
Q1	48%
Q2	22%
Q3	16%

Table 11. Disagreement with individual questions − feasibility

Question	Disagreement
Q1	40%
Q2	16%
Q3	19%

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Figure 1. Module unloading at liquified natural gas loading facility at ??? for Qatargas

(courtesy Fluor Construction and Fabrication, Amsterdam)

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Figure 2. Installation of complex pipe-rack module in Al-Jubail, Saudi Arabia, for Saudi Petro Gas Company (courtesy Fluor Construction and Fabrication, Amsterdam)

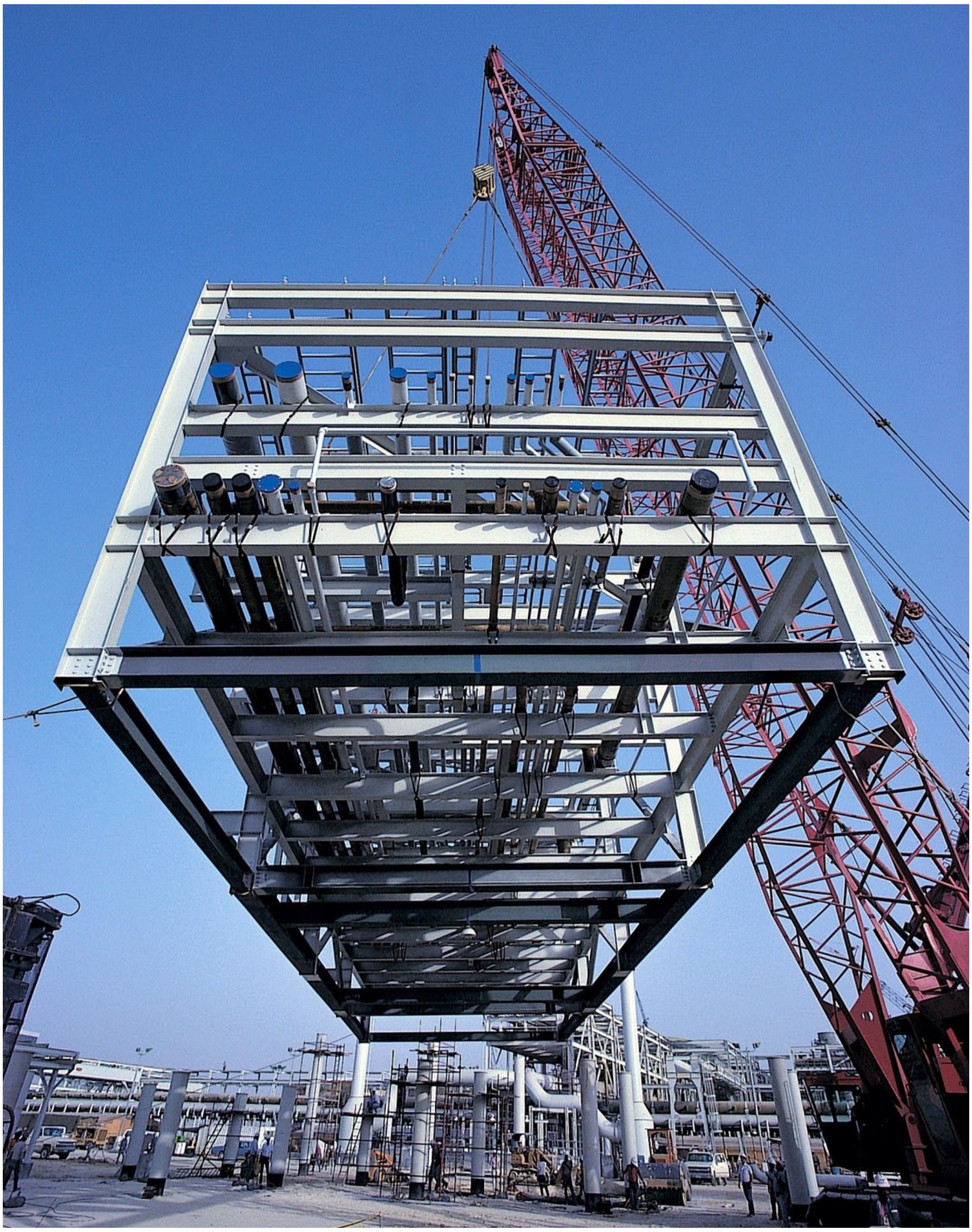

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Figure 3. Piperack installation in Freeport, Texas, USA for Dow Chemical Company (courtesy of Fluor Construction and Fabrication, Amsterdam)

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Figure 4. Heavy haul pipe-rack module on Sakhalin Island, Russia, for Exxon Neftegas Ltd (courtesy of Fluor Construction and Fabrication, Amsterdam)

Figure 5. Development of decision-support tool

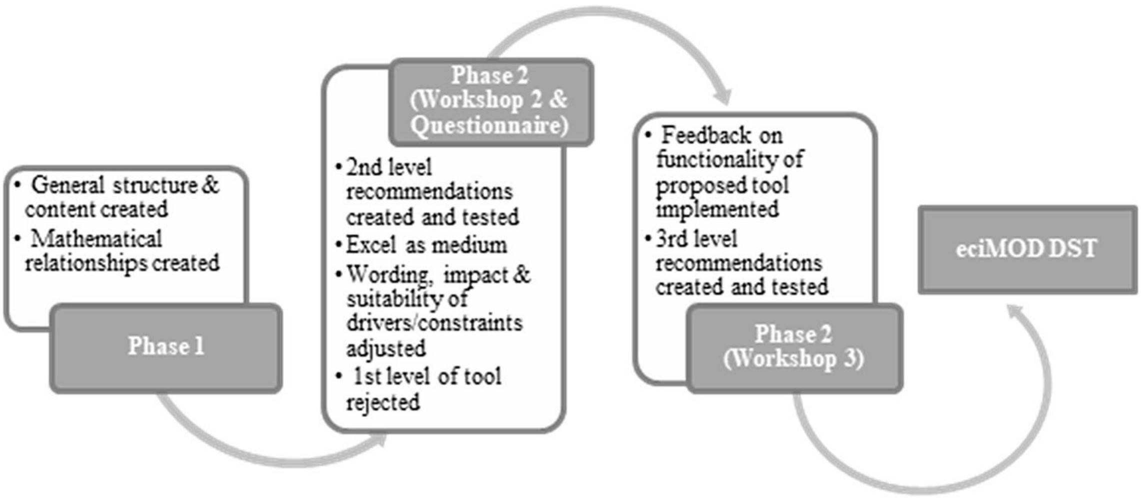

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Figure 6. Initial concept design of decision-support tool

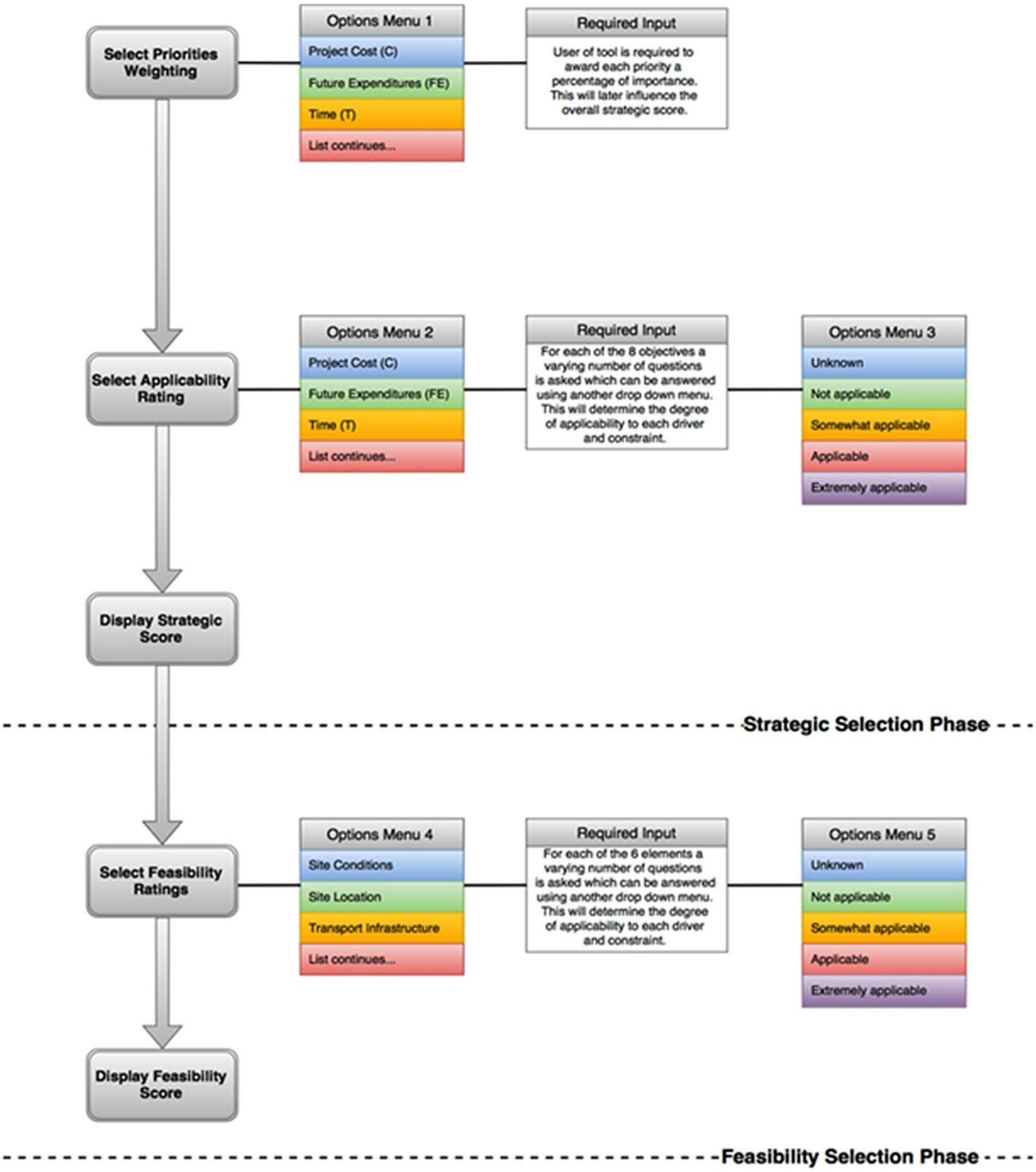

Figure 7. Full matrix used in analysis

	Total Project Cost			Operating Costs of Facility			Time schedule of the Project			Quality of Plant			Predictability of Expenditures and Completion Time			Workers exposure to onsite Working Conditions			Sustainability			Development of Local Content			Participant Disagreement
	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	
Participant A	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0%
Participant B	-	-	-	-	-	-	X	X	O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33%
Participant C	-	-	-	-	-	-	O	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33%
Participant D	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0%
Participant E	-	-	-	-	-	-	X	O	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33%
Participant F	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0%
Participant G	-	-	-	-	-	-	O	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	33%
Participant H	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0%
Participant I	O	X	O	O	X	X	-	-	-	O	X	X	O	X	X	O	X	X	O	X	X	O	X	X	33%
Participant J	X	X	X	X	X	X	-	-	-	X	X	X	X	X	X	X	X	X	X	X	X	O	X	X	5%
Participant K	X	X	O	O	O	X	-	-	-	O	O	X	X	O	X	X	O	X	X	O	X	X	X	O	43%
Participant L	O	X	O	X	O	X	-	-	-	X	X	X	O	X	X	O	X	X	O	X	X	O	X	X	33%
Participant M	O	X	X	X	X	X	-	-	-	O	X	X	X	X	X	O	X	X	O	X	X	O	X	X	24%
Participant N	O	O	O	O	O	O	-	-	-	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	100%
Participant O	O	X	X	O	X	X	X	X	O	O	O	X	X	X	X	O	X	X	O	X	X	X	X	X	29%
Participant P	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	4%
Participant Q	X	X	X	X	X	X	O	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	4%
Participant R	O	O	X	X	O	X	O	X	X	X	X	X	X	X	X	X	X	X	X	O	X	O	X	X	25%
Factor Disagreement	60%	20%	40%	30%	40%	10%	50%	10%	20%	50%	30%	10%	30%	20%	10%	50%	20%	10%	50%	30%	10%	60%	10%	20%	

Figure 8. Example of first-level recommendation in the decision-support tool

Recommendation A

*A weighted applicability score of **less than 0 has been calculated.***

'Based on the information that you have provided, the project is very unlikely to gain benefits from the adoption of modularisation. No adoption of modularisation is advised. It is suggested to get further information on all the elements for which you selected 'Unknown' or consider another construction method.'

Figure 9. Example page of decision-support tool software