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Modularisation for Construction: A Data Driven Approach

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Abstract

The construction industry is experiencing further industrialisation and embracing mass-customisation. The development of modularisation approaches to tackle product planning is crucial for the achievement of mass-customisation. However, research on modularisation in construction is limited. There is therefore a need to develop more advanced modularisation approaches to address product planning issues. Breaking down a modularisation problem provides a better understanding of its dynamics and drivers. This paper proposes an approach to address multiple modular drivers in construction. The modular drivers addressed in this paper include: technical specification, manufacturing and common unit. Multiple modularisation tools were utilised including the design structure matrix (DSM), the generational variety index (GVi), the coupling index (Ci), and the Cost Weighting (CW). These tools were utilised both for natural clustering and objective driven clustering. The modularisation tools were implemented on a plant-room case study. The work stresses and addresses the importance of understanding the fundamentals of a modularisation problem as well as the formulation of an effective solution.

Keywords: construction, modularisation, product planning, mass-customisation, technology strategy

1 Introduction

The construction industry is experiencing further industrialisation driven by a shift towards off-site construction and a growing interest in mass-customisation. In order to facilitate this industrial shift two capabilities are needed. Firstly, the industry has to acquire new manufacturing and automation capabilities (Marchesi et al. 2013, and Hook 2006). Secondly, the industry needs to define effective, flexible and efficient product systems that are adaptable to rapidly changing requirement conditions imposed by clients, technological development, business considerations and other corporate reasons. In response to these challenges, the construction industry is adopting modularisation strategies.

Modularisation allows for the clustering of different product sub-systems or components into modules to increase the flexibility of the overall product system (Borjesson & Holtta-Otto 2014). It is useful for handling product variations and reducing redesign work (Simpson et al. 2012). Modularisation enables quicker and easier reconfiguration of products to meet customised demands without massive alterations of the product or production operation. Despite the value of modularisation tools, research on their application to achieve further efficiency in construction has been limited (Gilbert et al. 2013). This is mainly due to limited advancements in off-site construction technology in the past years (KPMG 2012) and the lack of accessible real case studies. There is a need for further research in construction to understand how to manage product variations and achieve cost efficiency. Despite the existence of multiple modularisation tools, there is a challenge to determine effective tools for supporting efficient developments of modular products in construction.

This paper builds upon the work developed in Wee et al. 2017b, which explains that a modularisation problem may require addressing many modular drivers and that different modularisation tools are needed to satisfy them. In particular, the paper advances modularisation principles by exploring technical methods for the formation of a modularisation strategy in construction. Three modularisation drivers were simultaneously considered (i.e. technical specification, manufacturing and common unit). These drivers were addressed by utilising specific modularisation tools (i.e. the dependency structure matrix (DSM), the generational variance index (GVi), Cost Weightings (CW) and the coupling indexes (Ci)).

This research is part of a larger project, which aims at developing a framework to handle modular building system design including application of the Quality Function Deployment (QFD) tool (Wee et al. 2017a, and Wee & Aurisicchio 2018). The research is based on a case study of a modular plant-room design and has been conducted in collaboration with engineers at Laing O'Rourke.

2 Literature Review: Modularisation in Construction

Modularisation tools have been developed and frequently applied in many industries (Gann 1996, and Lawson et al. 2012). Historically very few of these tools have found their way into construction. However, as the construction industry advances and becomes more in line with a manufacturing process, there has been increasing opportunities for the adoption of these methods in construction. This paper refers to modularisation as the clustering of product sub-systems for the formation of a module (i.e. a product subsection). Modularisation is useful to support mass-customisation, which aims at meeting the demands of individual customers by facilitating high product variety with near mass-production efficiency. To realise mass-customisation, manufacturers tend to implement more efficient and flexible product designs and manufacturing strategies (Kreng & Lee 2004, and Suh et al. 2007). Modularisation can support mass-customisation through the development of modules that can be quickly assembled to produce a spectrum of differentiated products (Erixon 1996, and Kohlhase & Birhofer 1996).

The potential advantages of modular design, which integrates the benefits of standardisation with that of customisation have been well documented in the literature. The application of high quality modular design with emphasis on performance optimisation is typically needed in construction (Gilbert et al. 2013). The benefits of modular design are associated with the use of off-site prefabrication technologies that can support manufacturing of large quantities of volumetric building units under a stable factory controlled environment. These benefits are related to increased production efficiencies and shortened project lifecycles (Lawson et al.

2012, and You & Smith 2016), and reduction of product design risk as well as minimisation of the potential impacts associated with future changes in business requirements (Koh et al. 2015).

There are many modularisation tools available including the “functional flow block diagram" (Emmatty & Sarmah 2012, Hölttä-Otto 2005), the "dependency structure matrix" (DSM) (Hölttä-Otto 2005, and Ulrich & Eppinger 2008), the "modular identification matrix" (MIM) (Erixon 1996) and the "modular product platform" via the "generational variety index" (GVi) with “coupling index” (Ci) (Martin & Ishii 2002, and Simpson et al. 2012). This paper focuses on DSM, GVi and Ci, as these tools are better suited for tackling the specific modularisation drivers of interest in this research.

The dependency structure matrix (DSM) is a design tool for mapping systems interdependencies represented in matrix form. DSM can be used for the analysis of product architectures and engineering processes (Hölttä-Otto 2005, and Borjesson 2010). It utilises sequencing or clustering algorithms to organise the sub-systems of a system.

Modular product platforms can be effective for dealing with product design variances and uncertain future product requirements. They have been successfully adopted in industries such as automotive (Gann 1996). This design approach clusters common product sub-systems that reoccur across a product family and standardise them into a product platform. Its application has helped reduced costs associated with product development by using a handful of platforms to create a variety of product families (Pan et al. 2008, Simpson 2004, and Cuperus 2003). In particular, manufacturing and design costs can be reduced as each module has only a few unique features that need to be redesigned each time (Gilbert et al. 2013). A modular platform can be generated, for example, through the utilisation of the generational variety index (GVi) and coupling indexes (Ci). GVi supports the identification of product sub-systems, which are less likely to require redesign (Jiao et al. 2007). In particular, GVi indicates the amount of redesign required for future product designs and Ci shows how closely two product components are linked together. GVi can be developed through an adapted QFD model, while Ci is acquired through the development of a coupling matrix (Martin & Ishi 2002).

Despite the existence of various modularisation tools, there has been limited research on the application of these tools in construction (Gilbert et al. 2013). However, two notable works relevant to the construction sector are offered by Veenstra et al. (2006) and Gilbert et al. (2013). Veenstra et al. (2006) tackled modularisation and platform issues in the housing industry using GVi and coupling indexes (Ci) to identify segments of a residential house that could be turned into modules or platforms. The study emphasises that GVi and Ci together would support a better understanding of external design forces. Veenstra‘s research follows the decision rules set by Martin and Ishii (2002) for determining modules and platforms. In particular, product sub-system with no or low GVi are to be turned into fully or partially standardised platforms. Product sub-systems with low “coupling indexes–supply” (Ci-S) are to be considered for higher levels of modularisation. This work approaches modularisation and platform design by tackling product uncertainty and risks. It demonstrated the benefits of using GVi and Ci as tools for modular platform development in construction. Differently, Gilbert III et al. (2013) used axiomatic design together with product platform design for the development of modules for temporary modular buildings. The research adopted a methodology that suggests modules by grouping the common functional requirements and physical design parameters of an overall system. The methodology categorises modules into common and specialist modules. The essential function of buildings is captured by core modules, which basically act as a studio module and additional required features are designated to the specialist modules.

3 Methodology

A case study was carried out to address a multi-driver modularisation problem from a data driven approach. This approach involved the analysis of both qualitative and quantitative data. Three modularisation drivers were addressed: technical specification, manufacturing and common unit. Multiple modularisation tools were used in the research including: design structure matrixes (DSM), generational variety indexes (GVi), coupling indexes (Ci) and cost weightings. This modularisation research was conducted on a plant-room product (see Figure 1). The methodology of the study involved: 1) data collection for the product case to be studied; 2) addressing of the three modularisation drivers individually; and 3) integration of the three modularisation drivers.

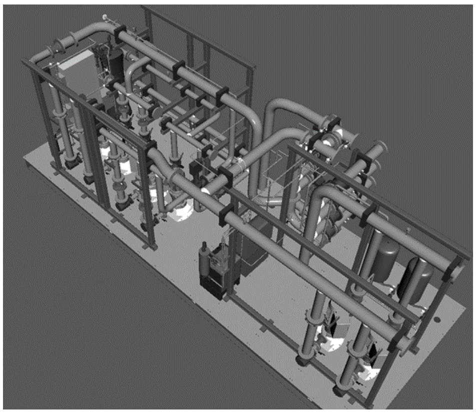

Figure 1: Plant room product (Source: Laing O'Rourke 2016)

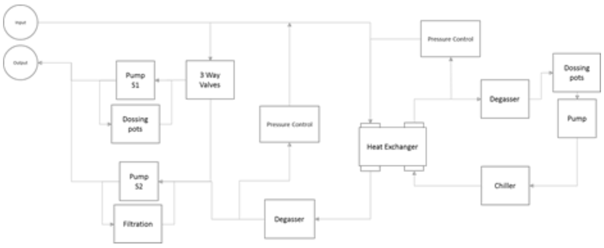

Figure 2: Simplified schematic

3.1 Data Collection

Product data and knowledge were acquired through document analysis and a reverse engineering methodology (Wee et al. 2017b). This involved the examination of existing product documentation and discussions with engineers from the collaborating company. The examined product documents included product manuals, CAD files, assembly animations, schematics and bills of materials. The type of information utilised in the case study is specific to each modular driver. A simplified version of the product schematic for the plant-room is illustrated in Figure 2.

3.2 Modularisation Drivers

The module drivers addressed in the reserach are presented next.

Technical specification: A component-based "function" Design Structure Matrix (DSM) model was developed using the Cambridge Advanced Modeler software (CAM 2014). Two pieces of information were utilised to build the model as follows: material flows and spatial preferences. The former was collected directly from the product schematic (see Figure 2). The latter is based on safety and maintenance information as well as operational preferences elicited from engineers in the collaborating company.

Manufacturing: A second component-based "function" Design Structure Matrix (DSM) model was developed to address the manufacturing modularisation driver. Four pieces of information were utilised to build the model as follows: physical connections, machining commonality, functional dependency and assembly sequencing. The data to build this model was collected from CAD drawings, product manuals, product schematics and assembly animations models.

Common Unit: An adapted version of Martin and Ishi methodology was implemented for addressing this modularisation driver (Martin & Ishi 2002). Specifically, a cost weighting element was added to determine the importance of each component to component relationship. By combining GVi, Coupling Index (Ci), and Cost Weightings (Cw) it is now possible to determine the relative cost impact of redesign of one product component on the overall product. The generation of GVi, Ci, and Cw is presented below.

- Generational Variance Index (GVi): GVi was generated though a modified QFD model (Wee et al. 2017b). GVi is calculated by summing up the potential redesign work as a result of changes in the product requirements. Information for the matrix was collected from interviews with engineers from the collaborating company.
- Coupling Index (Ci): A coupling matrix was developed using the methods proposed in Martin & Ishi 2002. The coupling matrix was used for the identification of the degree of coupling between two product components. The matrix generates two types of coupling indexes. The first, known as "coupling index supply" (Ci-S), establishes the level of design information supplied to a component. The second, known as "coupling index received" (Ci-R), details the level of design information received by a component. Information for the matrix was collected from CAD files and supported by information gathered through reverse engineering.
- Cost Weightings (Cw): Cost weightings were determined by the prices obtained on the basis of possible online purchases. The actual cost of the plant-room product was not used due to information sensitivity. Cw was used to illustrate the potential value of costing as an improvement to the traditional common unit method described in Martin & Ishi 2002.

3.3 Integration

The modularisation drivers were prioritised based on the preferences of the collaborating company, as explored in Wee et al. 2017b. The design resulting from the technical specification driver was compared against that of the manufacturing driver, then adapted to include features from the common unit driver.

4 Case Study: plant-room modularisation

A plantroom case study was used to examine the possibility of addressing multiple modularisation drivers. In order to tackle each modularisation driver, the nature of each driver must first be understood. Modularisation drivers can be categorised into three different types: natural clustering, objective clustering and restrictions drivers.

Natural clustering: These drivers target concentration of product or operational dependencies. This involves grouping together components that are naturally more closely associated with one another. For example, under technical specification components were clustered together based on their functionality or component dependency. Another example relates to manufacturing, which takes an operational or process perspective.

Objective clustering: These are strategic business drivers, which aim at achieving business objectives. One example is the common unit modularisation driver, which acts as a method for standardising sections of the product and developing a product platform. It can reduce redesign costs and increase business stability.

Restrictive drivers: These drivers often refer to external restrictions on a product, which limit the attributes of a module and are major contributors to the module definition. These drivers can include architectural aesthetics or transportation drivers.

Understanding the nature of modular drivers can support a reliable selection of modularisation tools. The technical specification and manufacturing modularisation drivers were tackled using DSM. The common unit modularisation driver was, instead, tackled with indexes.

4.1 Technical specification-led modularisation

This modular driver aims at providing the technical specification of a product system on the basis of functional variance. This can be analysed by investigating sub-systems to sub-systems dependencies. High dependency amongst product sub-systems means that the sub-systems have high functional reliance on each other. Therefore, it would be beneficial if they were clustered together into a module.

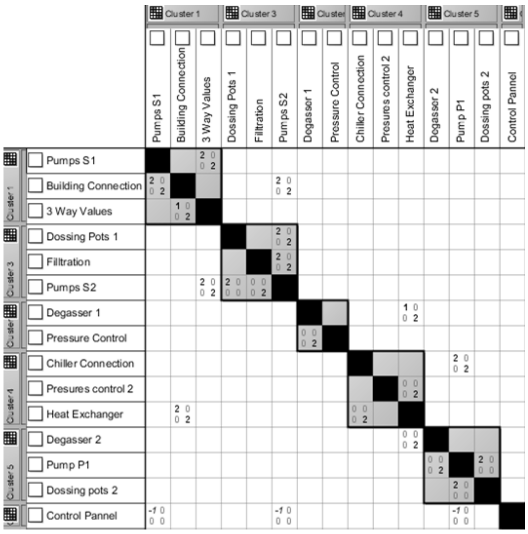

Figure 3: Dependency Structure Matrix (Technical Specification)

The DSM model was built using a total of 15 product sub-systems, which were mapped on to themselves capturing the plant-room's material flows and spatial preferences (see Figure 3). Sub-system to sub-system dependencies were labelled on a scale of 2 to -2, where 2 signifies a required dependency and -2 implies a detrimental relation. The CAM culturing algorithm was used to cluster sub-systems into modules based on the input dependencies. The partitioning feature was then used to determine the ordering of the modules. As can be seen in Figure 3, seven modules were recommended by the DSM tool with two modules composed by a single product sub-system (i.e. control panel and structure). Of the seven modules, the five main modules, i.e. those composed by at least two product sub-systems, are highlighted in the product schematic in Figure 4.

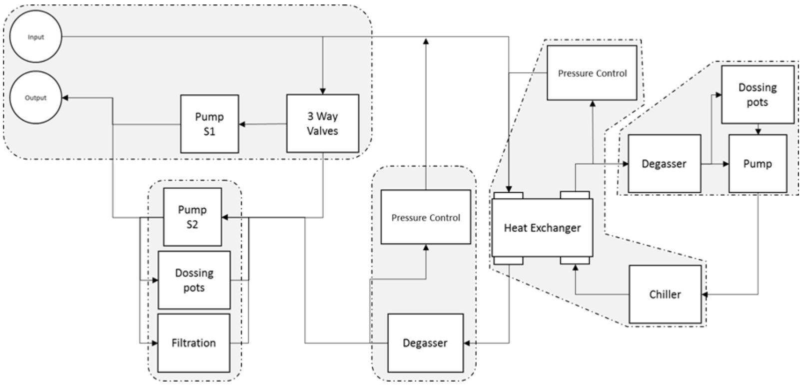

Figure 4: Clustering for the technical specification modular driver

4.2 Manufacturing-led modularisation

The objective of this modular driver is to support ease of manufacturing. This can be analysed by investigating operational dependencies. Similar to the technical specification modular driver, it would be beneficial to cluster components with high manufacturing operation dependencies.

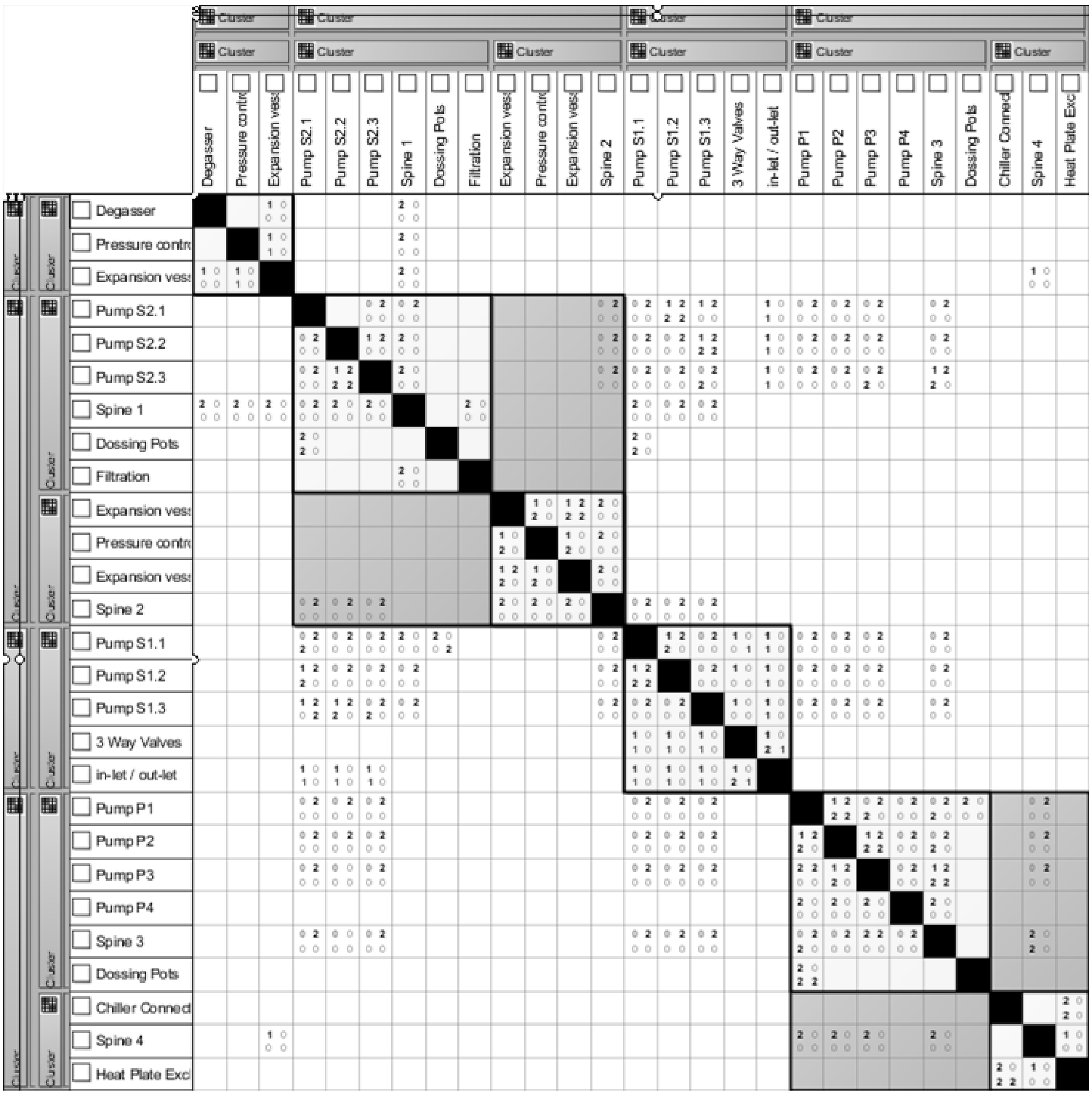

Figure 5: Dependency Structure Matrix (Manufacturing)

The DSM model was built using a total of 27 product components (Figure 5), which were mapped on to themselves based on consideration of physical connections, machining requirements, functional dependencies, and assembly sequencing. Component-to-component dependencies were labelled on a scale of 2 to -2, where 2 signifies a required dependency and -2 implies a detrimental relation. Components were clustered into modules based on input dependencies criteria. The partitioning feature was then used to determine the ordering of the modules. Based on these considerations, the DSM model provides a modularisation solution. Figure 6 illustrates the results on the product schematic, where the 27 product components were mapped on to their core modules.

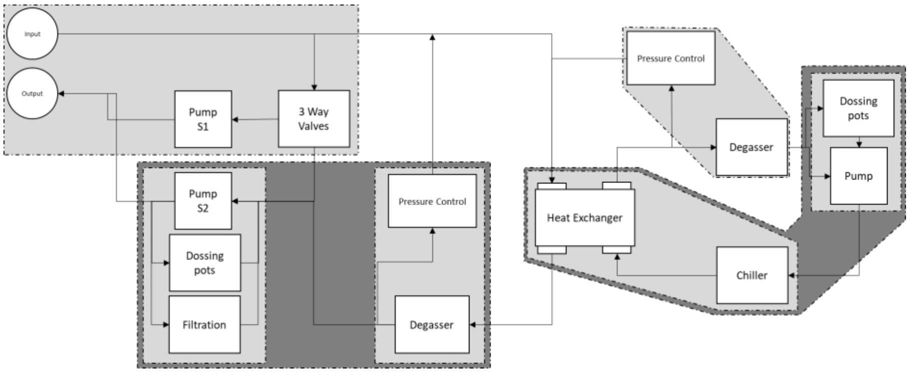

Figure 6: Clustering for the manufacturing modular driver

4.3 Common unit-led modularisation

This modular driver clusters product sub-systems which are more likely to change from one product generation to another. It can be used for the identification of sub-systems, which are ideal for standardisation and in turn for the development of a product platform.

A QFD model was developed to generate the GVi. Figure 7 provides an overview of the layout of the QFD-GVi model. GVi is a metric tool that approximates the likelihood and potential rework needed for the next product evolution. A coupling matrix (see Figure 8) was developed to generate Ci, a metric tool that indicates the level of coupling that is present between two product sub-systems. From this matrix the coupling index supply (Ci-S) and the coupling index received (Ci-R) can be extracted. Both the QFD-GVi matrix and coupling matrix were built using a total of 15 product sub-systems. Cost weightings (Cw) were also included to determine the importance of each sub-system to sub-system relationship. The resulting GVI, Ci-S, Ci-R and Cw are shown in Table 1.

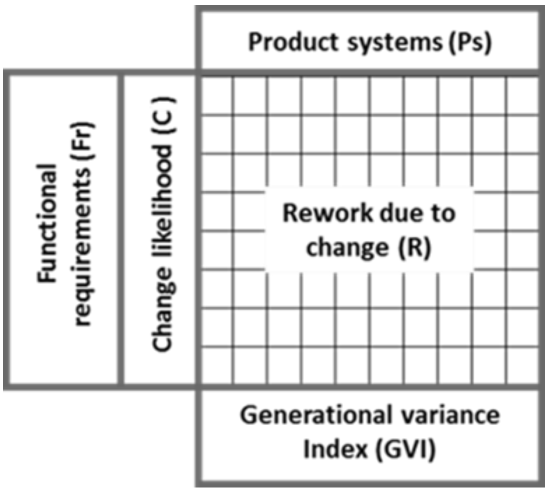

Figure 7: QFD-GVi Matrix Layout

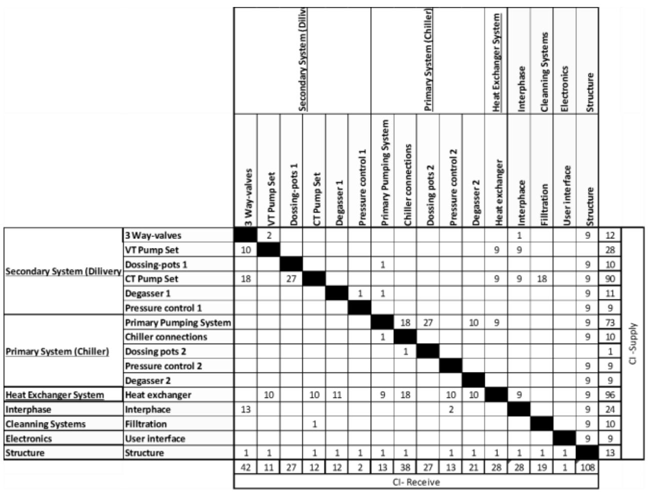

Figure 8: Coupling Matrix

Table 1: Indexes associated with each component

	CW	GVi	Ci-S	Ci-R	Old - Rc	(Ci-S) x (Cost)	(Ci-R) x (Cost)	New -Rc
3 Way-valves	7.43	16	12	42	FM	133	1765	FM
VT Pump Set	59.71	177	28	11	PM	1121	1106	
Dossing-pots 1	1	2	10	27	FM	79	1613	FM
CT Pump Set	59.71	177	90	12	PM	1414	1103	
Degasser 1	24.57	11	11	12	FS	118	1159	FS
Pressure control 1	15.43	16	9	2	FS	15	40	FS
Primary Pumping System	78.29	84	73	13	PM	1379	1039	
Chiller connections	6.57	1	10	38	FM	85	3273	FM
Dossing pots 2	1	2	1	27	FM	8	2115	FM
Pressure control 2	16.29	16	9	13	FS	16	1061	FS
Degasser 2	22.69	11	9	21	FM	23	1837	FM
Heat exchanger	103.14	40	96	28	PM	2839	1883	
Interphase	6.57	29	24	28	PM	136	2017	FM
Filtration	11.43	13	10	19	FM	71	1086	FS
User interface	28.57	27	9	1	FS	29	29	FS

From the data in Table 1, specific characteristics of each product sub-systems can be determined. Utilising the data in Table 1 and the recommendations on which product sub-systems are suitable for full standardisation (FS), or full modularisation (FM), the “common unit” can be identified (see Table 2). The new recommendations (New-Rc) represent an adaption of the recommendations (Old-Rc) proposed in Martin & Isshi 2002. Figure 9 marks the sub-systems identified for individual full modularisation and standardisation.

Table 2: Common unit recommendation rules

GVi	Martin & Isshi (2002)		New Index		Recommendations	Abbreviation
	Ci-S	Ci-R	Cost - Ci-S	Cost -Ci-R		
Low		Low		Low	Fully Standardised	FS
High		High		High	Partially standardised	PS
	Low		Low		Fully Modularised	FM
	High		High		Partial Modularised	PM

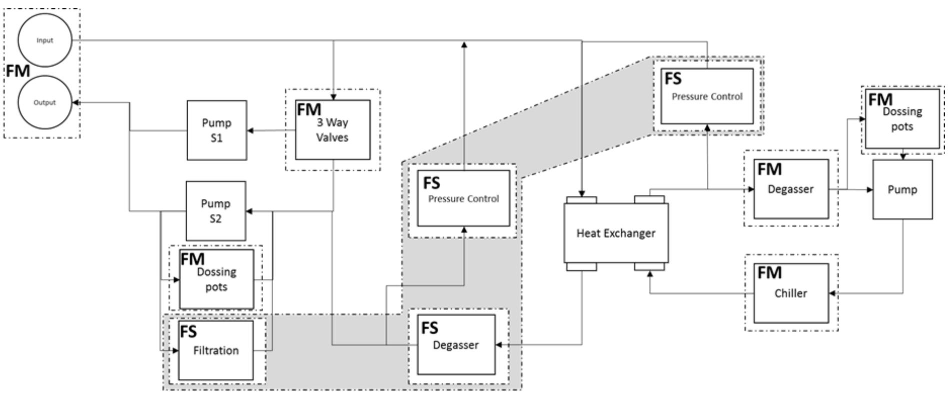

Figure 9: Recommendations for standardisation, individual modularisation and common unit.

4.4 Outcomes of the three modular drivers and integration

The three modular drivers pursued in this research produced different module clustering results, see Figures 4, 6 and 9. By tackling each driver individually, specific modularisation rationales were determined. The integration of the three clustering results produced the modularised design shown in Figure 10 where technical specification was prioritised followed by manufacturing and common unit considerations. Comparing the results of the technical specification and manufacturing modular drivers, modules 1, 2 and 3, marked in light grey in Figure 10, were identified as non-conflicting modules. It is noteworthy that module 3 is also recommended by the common unit modular driver. Further comparison of the results of the technical specification and manufacturing modular drivers also led to the identification of modules 5 and 6, marked in light grey in Figure 10, as non-conflicting modules. It is noteworthy that these two modules, matching with those recommended by the manufacturing modular driver, see Figure 6, represent a subset of the recommendation from the technical specification modular driver, see Figure 4. Two sub-systems, i.e. pressure control and degasser, were left floating since there is no strong rationale for clustering them, see Figure 10. Finally, modules 2 and 3 and modules 5 and 6 were further modularised into modules 4 and 7 respectively. This high level modularisation is recommended by the manufacturing modular driver and does not conflict with the recommednations from the other drivers.

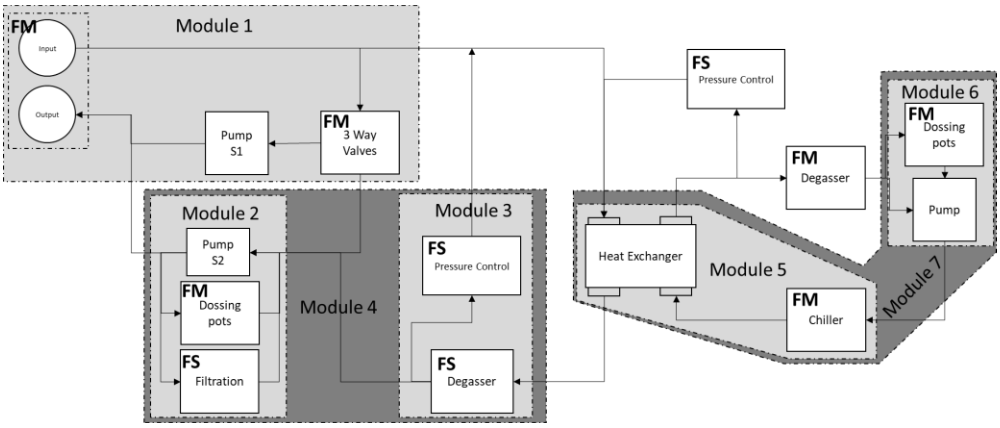

Figure 10: Integration of modularisation results

5 Discussion

This research contributes to the literature on mass-customisation in construction by showing how modularisation tools can be applied. The research provides new insights into modularisation drivers and the elements that affect the design and clustering of modular product sub-systems or components. This work is important to understand how to develop product solutions that address construction modularisation drivers. It provides a more advanced and multi-driver approach than those utilised by Veenstra et al. (2006) and Gilbert et al. (2013). Some valuable lessons can be drawn from this research as follows.

First, the utilisation of a data driven approach has permitted a more insightful analysis of the design space to support modular products development. It has helped identify possible design advantages by tackling a modularisation driver. For example, the identification of dependencies concentration (i.e. technical specification) for easy design management or the utilisation of indices to address design objectives.

Second, combining the results from the three modularisation drivers (i.e. technical solutions, manufacturing, and common unit), a valuable amount of design information can be used to support the development of a modular product. Product functionality, variety, manufacturing and standardisation have all been addressed in a singular solution.
Third, the work conducted for the common unit shows the value of determining which components should be individually standardised or modularised. The addition of a cost weighting variable adds an additional perspective to the traditional method of determining common units. This information is valuable to minimise the risk of redesign work.
Fourth, not all components are affected by all modularisation drivers (e.g. structural components are not affected by technical solution modularisation driver). Each modularisation driver led to the implementation of different modularisation models to include different product sub-systems or product components. For example, the product structures tend to be primarily affected by the manufacturing modularisation driver and not by technical specification. This is because the product structure components do not directly provide the product function (e.g. deliver water). A key limitation of this research is that it utilises one case study. Future work should expand to cover a variety of additional case studies and across a spectrum of construction products. This recommendation will help develop better and more encompassing modularisation strategies for construction.

6 Conclusions

Mass-customisation in construction is a multi-driver problem. Future modularisation work in construction needs to address this issue. Several modularisation drivers need to be addressed simultaneously and integrated into one encompassing solution. This research provides a strategy to tackle multiple modular drivers, which is essential to address modularisation problems in construction. In particular, a solution was developed to tackle three selected modularisation drivers (i.e. technical specification, manufacturing and common unit). Each modularisation driver was first addressed individually generating valuable design information for the formulation of the design strategy. The results were then integrated to form a singular modularisation solution that accommodates the requirements from all three modular drivers.

7 Acknowledgment

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