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The Technical and Commercial Impact of Engineering Changes in the Conceptual Housebuilding Industry

A case study at MorgenWonen

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Abstract

The housebuilding industry in the Netherlands is stressed due to availability, affordability and sustainability. This leads to a shift towards industrialised housing construction (IHC). MorgenWonen is a company in the Netherlands that has chosen the path of IHC. The current designs are a proven concept for MorgenWonen, however when constructive or engineering changes are made to the designs the impact of such a change remains unclear. The high interdependence between elements, their suppliers, and the processes cause uncertain outcomes during concept development. Therefore, this research aims to identify the technical and commercial impact of engineering changes to the housing concepts of MorgenWonen.

A Design Structure Matrix (DSM) and Domain Mapping Matrices (DMM) are used as supporting tools to analyse the impact of an engineering change. The DSM focusses on the dependencies between building elements, while the DMM's focus on the dependencies between the building elements and other domains, in this case suppliers and processes. Impact analysis of specific design changes and general analyses are done based on these matrices. The specific impact analysis shows the technical and commercial impact of the proposed design changes, whereas the general analyses show how interdependent certain elements are, where clusters arise, and which elements act as multipliers or absorbers of change.

The results show that the small and internal engineering change does not have great impact on the whole housing concept. The lead time is approximately two weeks and the amount of engineering hours does not exceed two hours. The impact becomes high, when the engineering changes are bigger and cross the boundaries of an element, especially when concrete elements are involved in the redesign. The lead times can go up to half a year or longer and the amount of engineering hours are between 60 and 150 hours, causing serious costs for the engineering change (new materials, processes, etc. excluded). Furthermore, the results show that the cluster analysis clusters the housing concept in three main clusters; the ground floor and first floor on the front of the house, the ground floor and the first floor at the back of the house, and the second floor and roof. Lastly, the change propagation analysis shows that the interior walls and doors absorb change propagation, whereas the stairs units, 'wet rooms', and meter-box are possibly change multipliers.

Going back to the main research question, it can be stated that the model (DSM and DMM's) is able to give an indication of the impact of proposed engineering changes. It can be concluded that, the concrete elements mainly drive the lead times of the engineering changes. Once a concrete element is involved in the engineering change the lead times go up to the maximum. Furthermore, it should be noted that the DSM does not capture all dependencies. Only three types of dependencies are used in this analyses, whereas more dependencies exist in real life.

Following these conclusions and findings during the research it can be recommended that MorgenWonen should focus on modularisation. Even when the DSM does not capture all dependencies it is already filled with a lot of dependencies, modularisation can minimize this. Furthermore, it is recommended to standardise process for engineering among the supply base to prevent unforeseen dependencies between elements, suppliers and processes and to give a better indication of lead times and engineering hours. Lastly it is recommended that MorgenWonen acts as a system's architect for future engineering changes, giving the concept development team the possibility to be the project manager of the engineering change.

MorgenWonen

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1 General introduction

The housing market in the Netherlands has to cope with some huge challenges. Three main themes can be identified: 1) availability, 2) affordability and 3) sustainability. According to the Ministry of Internal Affairs and Royal Relations (Ministerie van Binnenlandse Zaken en Koninklijksrelaties, BZK) the Netherlands faces a housing shortage of 279.000 houses in 2021 (BZK, 2022). Besides that, the demand is not expected to go down. Therefore, the minister sets the goal of building around 900.000 houses before 2030, meaning around 100.000 houses each year (BZK, 2022). Besides the shortages, affordability of housing is another mayor issue in the current housing industry. A report of the McKinsey Global Institute (Woetzel, 2014) estimates that 330 million households are financially stretched due to their housing costs or live in substandard housing conditions. Lastly, housing, as an aspect of quality of life, largely influences sustainable development. The potential for the housing industry to contribute to sustainable development through its construction, use, and demolition is very significant (Winston & Pareja Eastaway, 2008).

The current way of building houses will not suffice in the demand (availability, affordability, and sustainability) that is asked from the market. The need for productivity, yielding the most output with minimum input, is one of the key drivers towards industrialised housing construction. Compared to the old-fashioned style of construction, which is characterised by project-based, one-time constructions, industrialised housing construction focusses more on efficiency, optimalisation and the use of information and communication technology (Kedir & Hall, 2021).

MorgenWonen is one of these companies that has shifted its focus towards industrialized housing construction. It is a sister company of Royal VolkerWessels B.V., one of the biggest building conglomerates in the Netherlands. MorgenWonen builds houses in association with other sister companies of VolkerWessels. Each of the companies is responsible for one of the components of the housing concepts. Around 70% of the components are made by these ‘in-house’ VolkerWessels companies. Currently they are producing around 400 houses a year, but their goal is to reach 2000 houses each year. To manifest this scale-up, MorgenWonen focusses on concept development, not only within their firm boundaries, but over the whole supplier network.

1.1 General problem statement

MorgenWonen offers housing concepts that are made in controlled environments like factories. Currently there are four standard concepts (4.8, 5.4, 5.7 and 6.9m in width) that are offered by MorgenWonen to customers like real estate developers and housing corporations. However, changes are made to these standard designs through two driving forces, one internal and one external. 1) Internally, MorgenWonen continuously wants to evolve their housing concepts, improving on technical and organisational aspects. Technical improvements can be considered as optimising certain building elements, by optimising performance, reducing costs, and enhancing ease of installation at the construction side. Organisational improvements are the improvements that are made to optimise the process of MorgenWonen, including sales, work preparation, purchasing, transport, etc. 2) Externally, customers want to have some freedom in certain design choices. These buyer options are design choices that fit in the standard constructive design of the housing concepts, i.e. different cladding on the facade. However, when the constructive design of the housing concepts is changed due to the customer’s demand, re-engineering is needed. Therefore, these changes are called engineering changes.

The technical improvements and engineering changes are severe and change the constructive design of the housing concept. This means that certain elements of the housing concept must be re-engineered. However, these elements are highly connected with each other, meaning that a change in one element would likely result in a change in another element. The initial engineering change can propagate through the whole system, affecting other elements and multiple suppliers of those elements.

So, the problem lies with engineering changes in the design, either through concept development or customer demand. These changes affect the technical specification of the design. A change in one element causes changes in other elements, and these changes ask for re-engineering. This problem can be divided into two sub-problems. On the one hand, **assessing the impact** of an engineering change cannot be done without a proper model which includes technical, organisational and process aspects. On the other hand, **the responsibilities** among MorgenWonen and its 'in-house' suppliers regarding re-engineering of the changed components **are not determined**. An overview of this problem breakdown structure and the accompanying goals can be seen in Figure 1-1. More detailed descriptions of the problem statements can be found in the devoted theses of that problem statement.

The remainder of this thesis is devoted to the Master Civil Engineering and Management (CEM) regarding the second problem statement (left side of Figure 1-1). Simultaneously with this thesis, another thesis is written devoted to the Master Business Administration (BA) regarding the first problem statement (right side of Figure 1-1).

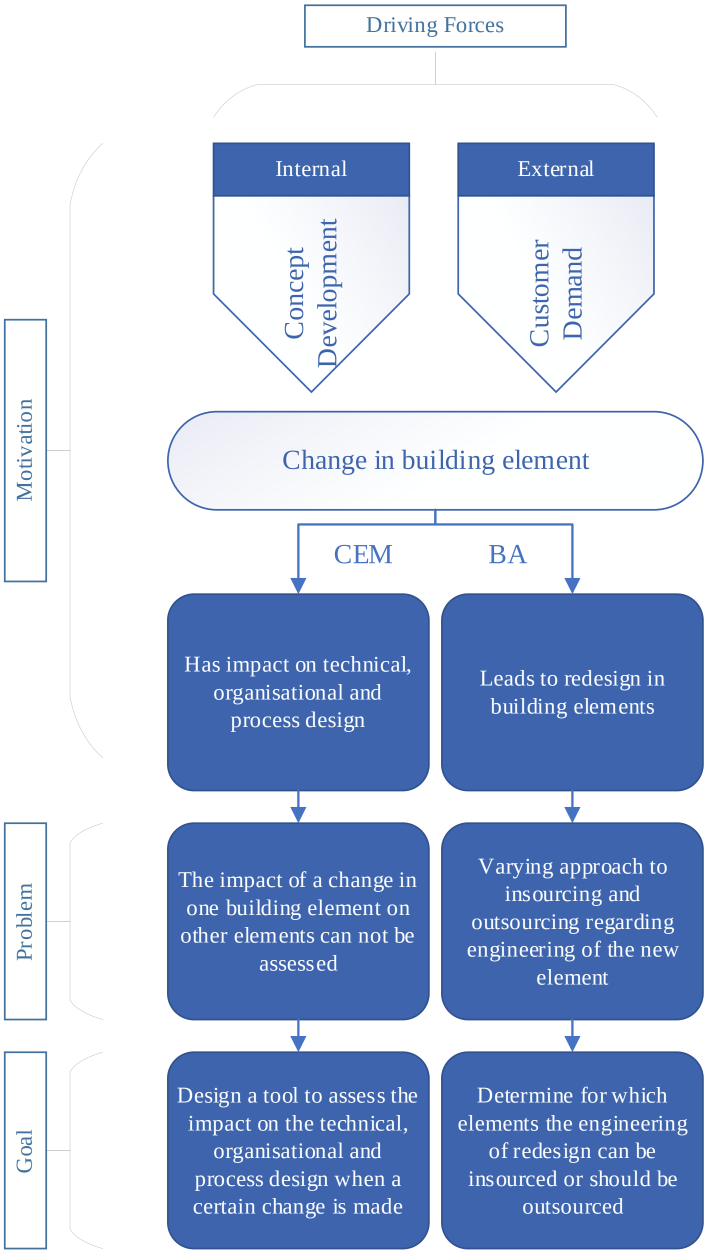

Figure 1-1, Problem Breakdown Structure

2 Introduction

2.1 Context and concepts

As mentioned in the general introduction the need for productivity in the housing industry is one of the key drivers for a shift towards industrialised housing construction (IHC). Industrialised housing construction is an umbrella term covering multiple approaches for innovative construction like prefabrication, modularisation and other modern methods of construction (Kedir & Hall, 2021). The use of these modern methods of construction changes the industry from 'project-oriented building contractors to production-oriented manufacturers' (Kedir & Hall, 2021, p. 111). Production-oriented manufacturing is mainly focussed on manufacturing lean and standardised products. So the development process should be productive, but also careful to meet customer expectations (Muffatto & Roveda, 2002). Therefore, manufacturers must think of variety, standardisation and customisation of their products.

Changes to products are made to meet new needs and requirements, and generally lead to an improved product. However, complex engineered products have highly linked components, where a change to one part results most likely in a change in other parts of the product, making the design-process very complex (Eckert et al., 2004). The changes emerging from customer requirements or concept development are called initiated changes, whereas changes occurring in response to the (re)design-process are called emergent changes. These changes can drive a product back in its development stage due to their uncertainties. According to Danilovic and Browning (2007) managers should identify, understand and reduce these organisational, product, and process uncertainties in order to add value to the final product. Furthermore, it is also important to recognise the need for (emergent) changes timely, to avoid high costs in later stages (Clarkson et al., 2004). However, this might be difficult due to the uncertainty of how an element is affected by a change and how the change in that element affects other elements. So in short, engineering changes lead to product innovation, however managing these changes can be considered very complex and uncertain.

A key activity of product development is the definition of a product architecture. A product architecture facilitates possibilities for cost savings, quality improvement and the ability to offer product variety (Ko, 2013; Wyatt et al., 2008). A product architecture can be described as the orchestration of different functional and physical components of the product and its interfaces to perform specified functions (Eppinger & Browning, 2012; Muffatto & Roveda, 2002; Ulrich, 1995). A more general term is 'system architecture', which also includes the architecture of other systems such as organisations or processes.

A product architecture fosters the interaction between different elements within a system and can therefore be used for change management within the whole system. The challenge in the change management process is to avoid so-called 'change avalanches' (Jarratt et al., 2002), where one change leads to multiple other changes, again leading to multiple other changes, changing the system dynamics of the product. To avoid this, good prediction of the system's behaviour is required (Eckert et al., 2004). A Change Propagation Analysis (CPA) can be carried out to analyse and predict the impact of these kind of engineering changes (EC's) (Rutka et al., 2006). Simple CPA-models capture the propagation of EC's with Boolean dependencies, but more advanced models can also entail some additional information within each dependency. Furthermore, the elements in the product architecture can be divided into three types; absorbers, carriers, and multipliers. Absorbers are elements that accommodate changes from other elements but only pass on a few (or rarely none). Carriers simply pass on changes from one element to another. Multipliers expand the change propagation and can therefore lead to change avalanches (Eckert et al., 2001).

Besides product architectures, literature also covers product platforms. These two terms might seem like the same concept, however they differ in definition. Where a product architecture refers to the relation between sub-elements or components of one end-product, product platforms refer to product components and how they are physically connected and common in different end products (Muffatto & Roveda, 2002). So for the industrialised housing industry a product architecture might refer to the relationships of all the components of one housing design, whereas a product platform refers to the connection of different components applicable in different housing designs. The focus in this research is on product architectures, rather than product platforms.

One tool to study product architectures and analyse change propagation is the Design Structure Matrix (DSM) (Rutka et al., 2006; Wyatt et al., 2008). The architecture of a product (or product architecture) defines how components are arranged and interact to perform certain functions. The DSM was firstly introduced by Steward (1981) and now widely applied for defining product architectures (AlGeddawy & ElMaraghy, 2013; Göhlich et al., 2018; Schmidt III et al., 2008) and change management (Zheng et al., 2019). An example of a DSM can be seen in Figure 2-1. The Design Structure Matrix is a $n \times n$ (n^2) matrix containing the components of a certain system, where the components in the row and column match in such a way that the diagonal of the matrix represents the components of the system. All the off-diagonals represent the possible interactions between the components of the system. This can be done either by a binary/Boolean system (interaction or no interaction) or a more qualitative system (identifying the kind of interaction). Figure 2-1 shows one of the most simple models of a DSM, only indicating the components (or elements) and whether or not the one influences the other. An entry in cell *i*,*j* indicates that component *i* influences component *j*. The kind of interaction depends on the entry value. So a DSM can be seen as a map of such a product architecture. The added value of a product architecture DSM increases as the systems becomes more complex, making it impossible for an individual to comprehend the entire system in a 'mental model'.

	A	B	C	D	E	F	G
Element A	A	1				1	
Element B		B		1			
Element C	1		C				1
Element D				D	1		
Element E		1			E	1	
Element F			1			F	
Element G	1				1		G

Figure 2-1, General example of a DSM (Wikipedia, 2022)

A DSM generally has the benefits of conciseness, visualisation, understanding, flexibility and possibilities for analysis (Eppinger & Browning, 2012). As Figure 2-1 shows, the DSM is a compact, visual tool that is easy to understand and adapt. Besides the matrix-shape of the DSM allows for multiple options for analysis. So, it is a tool used by engineers to assess the connections across elements in complex systems.

However, this type of DSM only gives insight into the interdependencies between components, organisations, or processes itself, but not into the intra-dependencies between these domains. Domain Mapping Matrices (DMM) cover the intra-dependencies between different domains of the system (i.e. the dependency of a component on a certain process) (Eppinger & Browning, 2012). DMM's are non-square matrices, with different domains on the rows and columns. The DMM is used to get more insight into the product architecture, not only looking at one system, but covering multiple domains.

After composing the DSM and DMM's for the housing design of MorgenWonen, an analysis can be done. One of the most common techniques for analysing a DSM is clustering. Clustering can be done by the number and strength of interactions of certain components or by finding common suppliers. There are two conflicting goals of clustering. The first goal is to minimize the size of the cluster (otherwise you could say that the whole system is one cluster). The second goal is to minimize interactions outside of the cluster. So the overall goal of clustering components of complex systems is to create small modules or sub-systems with few external interactions and many internal interactions (Rechtin, 1991). An objective function can be derived from this considering both the size and external interactions of the cluster.

Lastly it is important to note that changes to components within the system could lead to new dependencies between components. This means that the system is dynamic, not static. So the consistency of the product architecture DSM depends on the tolerance margins of the components of the system. Eckert et al. (2004) suggest that tools like DSMs could still support design-by-redesign, next to only giving insights in the design of the original product architecture. However, one should be aware of the dynamic nature of change propagation within a system in a static product architecture model.

2.2 Vision and Challenges at MorgenWonen

MorgenWonen is one of the construction companies in the Netherlands that shifted its focus towards industrialised housing construction. They make use of the factories within VolkerWessels to produce most of the components of their houses. Their challenge is to build affordable, qualitative, comfortable and sustainable houses. This is incorporated in their mission to make the right choices today, so that we can life in a sustainable environment tomorrow (MorgenWonen, 2022).

Currently, four standard housing concepts are offered and realised by MorgenWonen, with a width (beukmaat) of 4.8m, 5.4m, 5.7m and 6.9m. The house is built up with mostly concrete elements. A visual representation is given in Figure 2-2. The vision of MorgenWonen for their industrialised housing construction is a move towards automatisation with an eye for customer requirements. The automatisation is captured in the standard designs, however MorgenWonen wants to give the opportunity to clients to vary within these four standard designs. Besides giving the opportunity for clients to vary, continuous concept development is a key driver to accomplish the mission and vision of MorgenWonen.

Figure 2-2, Visual representation of a MorgenWonen housing design

However, MorgenWonen faces the challenge that the customer requirements and concept development ideas are hard to implement in the standardised engineered designs of their houses. So based on their vision there are two opposing goals. MorgenWonen wants to move towards automatisation through standardisation, but offer freedom in variety for customers in their designs and continuously develop their designs.

2.3 Problem Statement

The process of developing an alternative conceptual housing design for MorgenWonen appeared to be difficult. As mentioned in the introduction, these complex engineered products have highly linked components. So a change in one of the components most likely results in a change in other components (Eckert et al., 2004). So translating this to IHC, a change in one of the building components of a MorgenWonen house would result in a modification of multiple building components in the whole housing design, leading to technical design changes, organisational interactions and multiple processes with differing processing times.

Applying changes to the designs of MorgenWonen currently leads to uncertain outcomes. What appears to be a minor change in the design could possibly lead to multiple technical changes, with a lot of supplier involvement and long processing times. These indications are now based on judgements of the concept development team. So the underlying problem here are the undefined interdependencies of the housing components and intra-dependencies with the suppliers and processes. When one of the components in the conceptual design is changed, it is unknown which components affect other components and how they do so. These relations are described in a product architecture. However, such a product architecture, indicating the impact of a change in one of the building components of MorgenWonen houses, is not yet developed.

2.4 Objectives and Scope

This research aims at defining the mutual interdependencies of the components within the designs of MorgenWonen houses and their relations with suppliers and its processing times. This should give an indication of the impact of an engineering change on the housing designs. A product architecture DSM is composed to give insights in the system dynamics of the different components of the house. The DSM should give insights in the impact of variations in the current design rather than the possibilities for complete re-design. A product architecture DSM is not applicable for such purposes (complete re-design), due to the static nature of the model. A complete redesign would also impose new interactions between different components, while a variation on one of the current designs does not. For this research a product architecture DSM is made for the 5.40m design of MorgenWonen. Furthermore, to capture the organisational impact and the processing times of certain changes DMM's are composed for the organisational supplier network and processes. The combination of the DSM with the DMM's give an indication of the impact of a design change on the other elements of the design, the supplier network and the processing times. A model is developed to assess the engineering change based on the DSM and DMM's. The insights given by this model serve as support in the decision-making process for concept development or client demand. The outcomes are merely an approximation of the impact on the design in best-case scenarios. The engineering changes used in this research are based on the concept development road map, since these are known and expected engineering changes.

2.5 Research Questions

To achieve the objective of this research the main question to be answered is as follows:

What are the technical and commercial impacts of engineering changes on the concept of MorgenWonen houses?

This question mainly focusses on the 'impact' of certain engineering changes. This impact on the design is defined as the direct and indirect effects of an element on its environment, regarding other design elements, suppliers and processes, as a consequence of an engineering change within that element. The definition of technical and commercial impact are given later in this paragraph.

The main question can be answered by looking into the following sub-questions:

First of all the dependencies within the technical design elements should be identified. The technical design elements are the elements out of which the whole house is build. One might think of floor/façade elements or bathroom/toilet units.

1. *Which technical design elements have to be incorporated in the impact analysis?*
2. *What are the constructive, spatial and installation interdependencies within the technical design elements?*

Next the dependencies between the technical design elements and the supplier network of MorgenWonen should be mapped. The supplier network consists of production suppliers and engineering suppliers.

3. *How does the supplier network of MorgenWonen look like?*
4. *How do the technical design elements relate to the supplier network of MorgenWonen?*

Thirdly, the processing times of each process related to certain changes in technical design elements are determined.

5. *Which processes take place from design to manufacturing within MorgenWonen?*
6. *What are the lead times and engineering hours for the engineering changes?*

Lastly, the data within the DSM and DMM's are validated by a case study. The design process of changing the width of the design to 4.8m is taken as a reference to validate the product architecture models. In this way the needed engineering hours, processing times, and technical dependencies are calibrated to reflect a realistic and good interpretable data. Hereafter, several engineering changes expected by the concept development are applied to the models.

7. *Do the product architecture models reflect reality when expected engineering changes of the concept development team are applied?*
8. *Which general conclusions can be drawn from the impact analysis?*

Answering these sub-questions should give a basic understanding of the impact of a design change in the MorgenWonen houses. The impact of an engineering change is proxied according to six indicators, divided in two classes; the technical impact with 1) the constructive, 2) spatial, and 3) installation dependencies within the technical design elements, and the commercial impact with 4) the number of suppliers involved in redesign, 5) the amount of engineering hours needed for the redesign, and 6) the lead times of the whole process. Figure 2-3 on the next page gives an overview of these proxies and show why they are important in the analysis. An overview of the research motivation, problem, objective and questions can be seen in Figure 2-4.

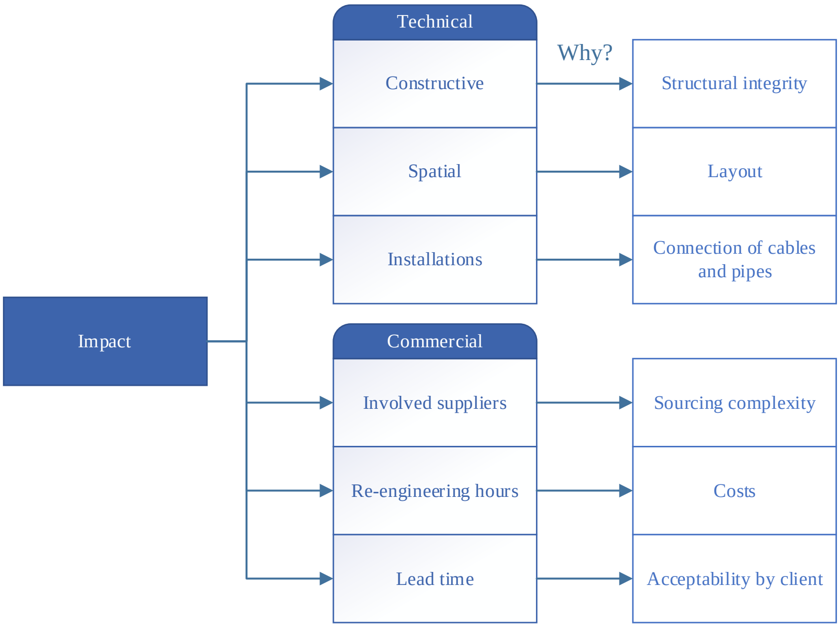

Figure 2-3, Proxies for impact

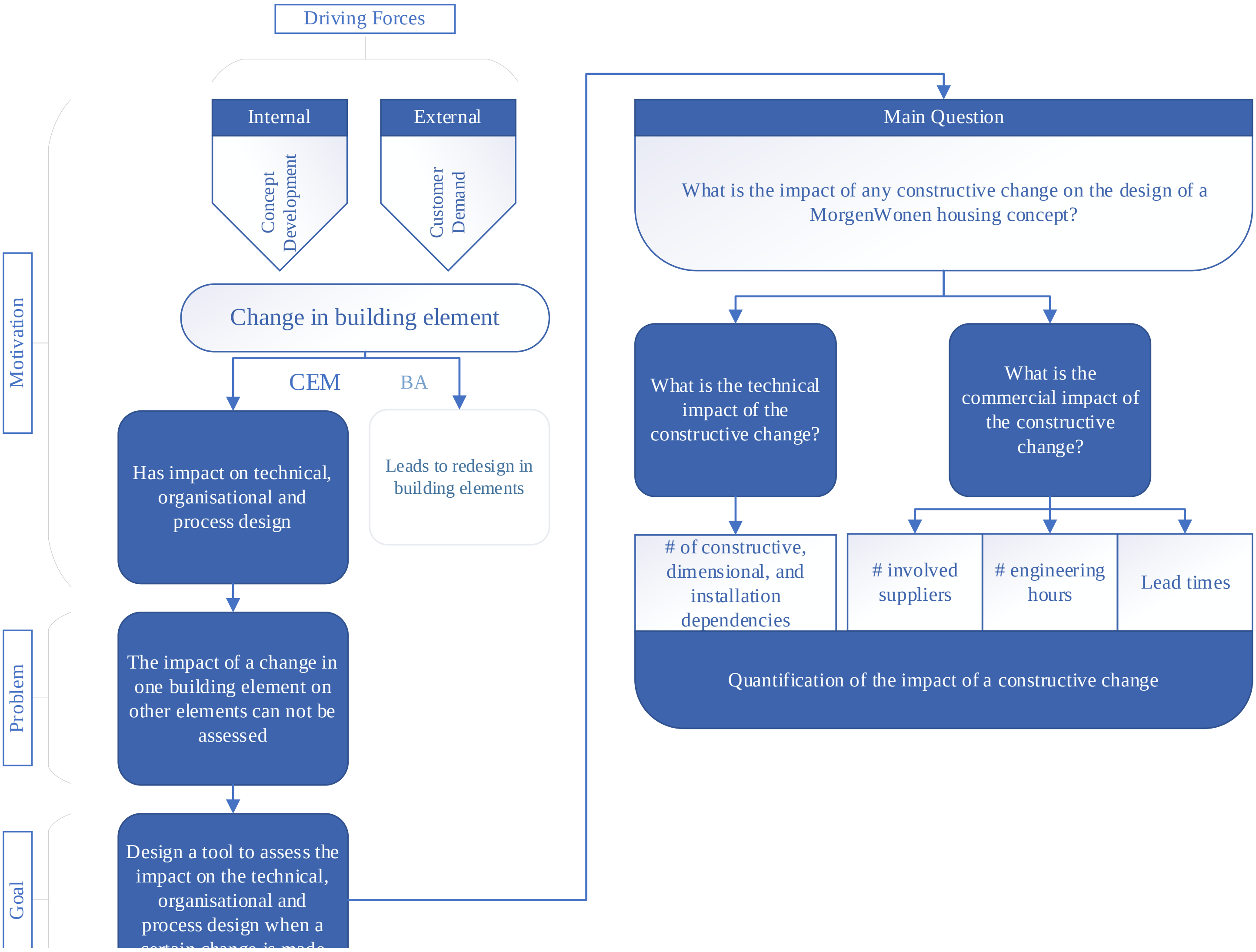

Figure 2-4, Research framework CEM

2.6 Reader manual

The remainder of this thesis is structured as follows. The next chapter describes the methodology, in which it is described how a DSM and DMM are made, calibrated, validated., and how they are used for impact analysis and general analysis. Next, the data and results of this research are given in chapter 4, followed by the discussion and suggestions for further research in chapter 5. Chapter 6 and 7 cover the conclusions and managerial recommendations. Lastly, chapter 8 gives statements about the scientific contribution of this research.

3 Methodology

3.1 Technical Design Elements

To answer sub-questions 1 and 2, a Product Breakdown Structure (PBS) is composed for the 5.40m design of MorgenWonen. The PBS is based on design documentation and specification and is complemented in cooperation with the concept development team of MorgenWonen. The level of granularity is based on the expert judgement of this team. Furthermore, a Design Structure Matrix (DSM) is used to identify the interdependencies of the building components of MorgenWonen houses.

Other tools can also be used to model dependencies within complex systems. The House of Quality (HoQ) is also a matrix-based tool that links product attributes with product parameters (Koh et al., 2012). The HoQ has a triangular 'roof' structure to model the functional dependencies between product parameters. However, these functional dependencies are assumed to be symmetrical due to the nature of the triangular roof. A DSM or DMM models the inter- and intra-dependencies of elements within and across domains in a square or rectangular matrix respectively. This allows for modelling non-symmetrical dependencies, which are also expected in the housing designs of MorgenWonen. Furthermore, model-based systems engineering (MBSE), is described as a model-centric approach to capture a system in a coherent model (Ramos et al., 2011). MBSE shifts the focus from document-based project control to model-based project control, entailing much more information than needed for change propagation methods. Therefore, this research focusses on DSM and DMM methods to model the dependencies within the system of MorgenWonen housing designs. The first two sub-questions only refer to the interdependencies of the technical design elements, therefor this part of the methodology only focusses on composing a DSM. The general steps of building, analysing and applying a DSM and DMM are based on the book of Eppinger and Browning (2012).

3.1.1 Composing a Design Structure Matrix

To compose the DSM, the six steps of Eppinger and Browning (2012) are followed. An overview of these steps can be seen in Figure 3-1.

Figure 3-1, Composing a DSM

First the system boundaries are defined. As mentioned earlier, this is done with a PBS. The PBS starts with the product as a whole and decomposes this product into sub-systems, which are again decomposed into elements of these sub-systems and so on, until a certain level of detail is accomplished. For this research, the design of the 5.4m house of MorgenWonen is taken as the whole system. This design is decomposed into sub-systems based on design documentation, specifications and discussions with design and concept development teams of MorgenWonen. So all elements of the 5.4m house of MorgenWonen lie within the system boundaries

Secondly, the dependency types of the DSM have to be identified. The example given earlier in this report only states whether there is a dependency or not. However, this is a rather simplistic way of applying a DSM and does not allow for in depth analysis in later stages of this research. Therefore, other types of dependencies are included in the composition of the DSM as well. Schmidt III et al. (2009) use three types of dependencies in their analysis of constructing school buildings for the future; structural dependencies, spatial dependencies and service dependencies. Veenstra et al. (2006) specify building interactions according to its technical elements (i.e. load-bearing), and its spatial uses. For this research we adapt, but slightly change, these types of dependencies. First of all, *constructive* dependencies are assessed and include things like changes in structural integrity. Secondly the *spatial* dependencies are assessed which are mainly described by changes in layout of the design. Lastly, *installation* dependencies are examined and these include any interaction including ventilation, water, electricity, etc. Other dependencies discussed by Eppinger and Browning (2012), like material flow or information flow, are not relevant for this research.

Thirdly, the strength of the dependencies are defined. Eppinger and Browning (2012) suggest a scale between -2 and 2. However, this is not applicable in this DSM, since a change in one component will not lead to a negative change in another. The change will either have (in different degrees) or not have an impact on other components. The strengths are defined as Boolean, solely indicating whether or not there is an interaction between two elements. The strengths of the dependency will be dependent on the type of change. The actual value will be dependent on expert judgement from the concept development team.

After identifying the strength of the dependencies, symmetry is defined. Symmetric interactions refer to the phenomena that component A affects component B and component B affects component A. In most DSM models symmetric interactions are expected. However, in this research dependencies do not necessarily have to be symmetric.

Granularity refers to the level of detail, and thus richness of the model. A lot of detail in the DSM model would give a more realistic representation of reality. However, a trade-off must be made between this level of realistic representation and comprehensiveness of the model. As a rule of thumb, twenty to fifty components allow for a realistic representation while maintaining comprehensiveness (Eppinger & Browning, 2012). Again the PBS serves as input for the granularity of the model. The level of decomposition of the sub-elements of the housing design determine the number of elements in the model.

Lastly, the interactions themselves are identified and documented in the matrix. The same methods to obtain the data are used as in the PBS. Product documentation like design drawings and technical drawings are used for preliminary identification of dependencies. Discussions with subject experts are used for more in-depth analysis of the dependencies. The actual documentation of the DSM is done with the use of software from Ratio-case (Ratio-case, 2022). The other parts of the model are based on the open-source software packages of Python.

3.2 Organisational Supplier Network

To answer sub-questions 3 and 4 the supplier network of MorgenWonen must be identified. This is done in an organigram of the suppliers including suppliers for production and engineering of the MorgenWonen houses. Once the supplier network is mapped, the dependencies between suppliers and the design elements (identified in the previous sub-questions) are linked. These links are modelled in a DMM, where each column represents a design element and each row a supplier.

The system boundaries of the DMM are defined by the PBS and the supplier network organigram. The same system boundaries for the design elements are taken to ensure consistency between the DSM and DMM models. The suppliers are based on the organigram and only go up to first tier suppliers of MorgenWonen.

The types of dependencies are defined in this DMM by either production or engineering. Furthermore, the DMM only states whether or not a supplier is involved in supplying a certain element or engineering service to MorgenWonen without considering interaction strengths. Symmetry is not applicable to a DMM since it is not a square matrix but a rectangular one, unlike a DSM. The level of granularity for the design elements are the same as in the first two sub questions. The level of granularity for the suppliers goes down to the organisational level, rather than design teams or individuals within an organisation.

The dependencies are again modelled in Python using software packages from Ratio-case as a basis for modelling the DMM. Other open-source software packages are used to complement the model to give more insight.

3.3 Processing Times

Sub-questions 5 and 6 are answered by identifying the processes involved in re-designing elements due to engineering changes. These processes are identified by semi-structured interviews with the 1st-tier suppliers of MorgenWonen. The processing times are determined by small, internal changes, medium changes and large changes to the elements, based on examples specific to those elements. I.e. for the façade elements a small, internal change would be the change of location of the embeds, a medium change would be to relocate or add a recess to the element, and a large change would be complete new dimensions of the element. A small change would only incorporate some extra preparation, a medium change also includes extra engineering work, while a large change also includes supplying new asset specific equipment. For all the suppliers it is determined how long the redesign process takes when a certain change is made to the element. An assumption is made that every engineering change has an initial lead time at MorgenWonen of 2 weeks with 0.5 FTE of engineering hours to start up the process.

3.4 Data Calibration, Verification and Validation

A calibration of the DSM and DMM is done based on applying the models to the real life case of re-designing a 5.4 housing design to a 4.8m design. The technical impact, involved suppliers, re-engineering hours, and lead times of all the processes are calibrated to fit the real life data of this particular redesign. However, since this re-design process had a lot of flaws, the data for calibration can also be flawed. Therefore, the re-design process is taken as a baseline but accompanied with expert judgement from the concept development team to determine the technical and commercial impact more exact.

Once the first calibration of the data is done, a verification is carried out to check how well the data suits reality. A focus group is organised in which employees of MorgenWonen get the exercise to determine what the technical and commercial impact is according to the above mentioned proxies for a certain engineering change in the design. The outcomes of this exercise are compared to the model outcomes. The model is verified when the values for the proxies are reasonably in line with each other. An internal validation of the model is done by setting some data points to the extremes and check for logical outcomes, i.e. a null-entry in the dependency matrix should lead to an impact of 0 between those components.

3.5 Impact Analysis

Eventually the impact of the engineering change is captured by combining the DSM and DMM's. The output of the models should give an indication of the direct and indirect effects in terms of changing other elements, number of suppliers involved and the processing times. The impact for the expected engineering changes by MorgenWonen are determined in this section. These engineering changes are based on the concept development road map of the development team.

Next the impact of the expected engineering changes is determined. This is done by determining the number of affected elements, number of involved suppliers, engineering hours and the lead time of the whole process. A conceptual model of this analysis can be found in Figure 3-2. It can be seen that the user of the model first has to identify which element or elements change due to the expected engineering change (initiated change). The involved suppliers, engineering hours and lead time of this engineering process is determined based on the collected data. Besides the affected elements are determined based on the engineering change. When a small, internal engineering change is applied, no other elements are affected. However, when a medium or large engineering change is applied, the user of the model has to determine if all the elements with a dependency on the changed element, are also dependent in this specific engineering change, and if so, how big this engineering change is; small, medium or large. Next, all the steps are gone through again, however with a few modifications and assumptions. 1) The affected elements in earlier loops are not taken into consideration anymore, since these elements already change, and are therefore accounted for. In theory one might say that in an earlier iteration the engineering change is small, but in a later iteration the engineering change to that same element might be medium or large. However it is assumed that in practice this will not be the case, since the engineering changes will always converge from large to small ones. 2) The largest lead time of an engineering change is taken as the lead time of the whole process of re-engineering. Here it is assumed that through this tool all the processes are known up front, and that the initiation of these processes can all start in early phases of the re-engineering process. 3) The number of involved suppliers are not double counted, since it is assumed that the impact of an engineering change is the same when a supplier is involved for either one, two, three, etc. elements.

The expected engineering changes which are used for the analysis are the following:

- Add standard recess in interior walls for sockets,
- Add prefab meter box to the design,
- Change entrance from front façade to side wall

It should be noted that the four proxies (affected design elements, suppliers involved, engineering hours and lead times) are not mutually independent of each other. For example, more suppliers involved in the engineering change cause more external communication and thus longer lead times. Therefore, it is important to note that the proxies show the direct and indirect effects of an engineering change and thus give an indication of the impact. They should not be summed or grouped into one formula to avoid double counting.

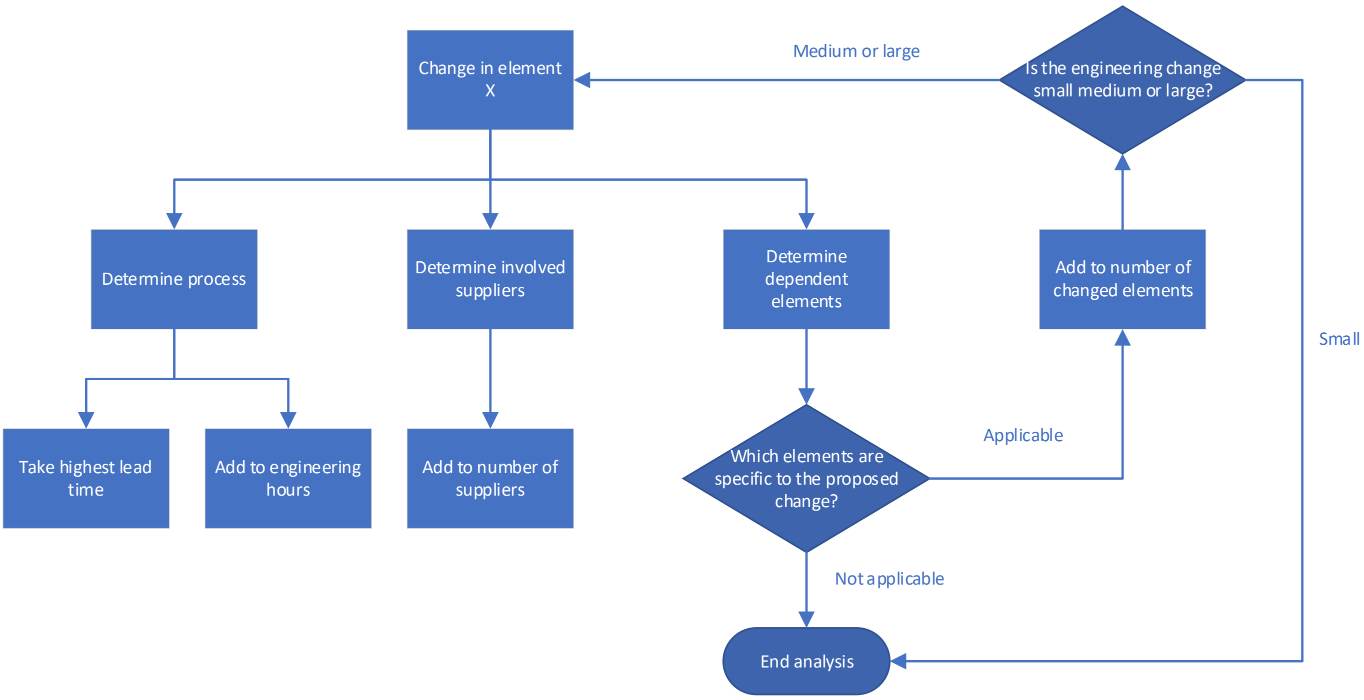

Figure 3-2, Conceptual flow diagram for impact analysis

3.6 Validation

A validation of the engineering changes is carried out to check whether the model output reflects reality and whether the model can capture the full impact of the engineering changes. In this part it becomes clear if the proposed engineering changes are actually of static or dynamic nature, when looking at technical and commercial dependencies. The validation is based on in depth discussions with the concept development team of MorgenWonen.

3.7 General Analysis

Lastly, a general analysis is done to get some insights in the dynamics of the product architecture and change propagation paths of the MorgenWonen housing concept.

First of all a clustering analyses is carried out to give insight into the highly impactful elements within the concept of MorgenWonen. This analysis clusters elements in such a way that the cluster is as small as possible and has the least interactions with other clusters. The elements that are not clustered with other elements are called 'bus-elements' and connect the clusters with each other. A standard clustering algorithm for matrices is provided by Ratio-case and used for this thesis to identify which elements could be grouped into modules and which are bus-elements where standard interfaces are recommended. The clustering algorithm is based on the Markov Clustering Algorithm (MCA). This algorithm, as described by Van Dongen (2000, p. 6), searches for the natural groups in a graph (G) in such a way that "a random walk in G that visits a dense cluster will likely not leave the cluster until many of its vertices have been visited.". The algorithm promotes flow where the 'current' is high, and demotes flow where the current is low. In this way the vertices between the clusters (with low current) are diminished and clusters arise. A visual representation can be seen in Figure 3-3.

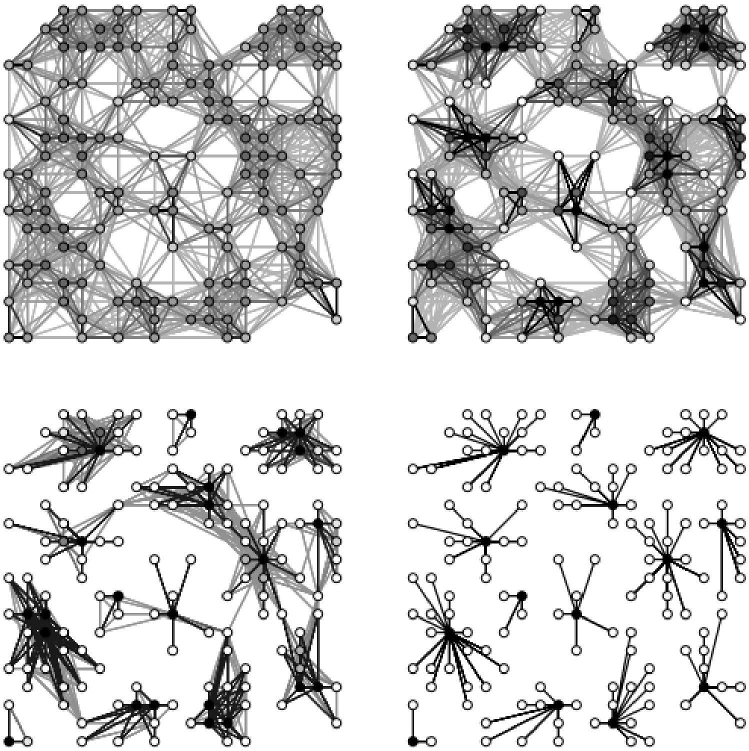

Figure 3-3, Successive stages of the Markov Clustering Algorithm (Van Dongen, 2000)

The cluster analysis is done for four DSM's. The first analysis is done based on the DSM with all types of dependencies. This analysis will show which elements are highly connected with each other within the whole design. The other three analyses are done based on DSM's with one type of dependency (structural, spatial, installations). These analyses will show how elements are connected to each other within certain types of dependencies.

Secondly, elements are categorised within three different groups; absorbers, carriers, multipliers. These three groups indicate whether the element absorbs, propagates or multiplies changes to other elements in the design. This gives an indication about the highly impactful (multipliers) elements and the elements that could easily be changed without much impact on the rest of the design (absorbers). Suh et al. (2007) introduce a Change Propagation Index (CPI) which measures the degree of propagation for an element in a complex system. The CPI is calculated according to Equation (1):

$$CPI_i = \Delta E_{out,i} - \Delta E_{in,i} \quad (1)$$

where the change propagation index of element i is calculated by the amount of elements that i is affecting ($\Delta E_{out,i}$) minus the amount of elements that i is affected by ($\Delta E_{in,i}$). This will result in a CPI that is either smaller, equal to or larger than 0. A CPI < 0 indicates an element that absorbs change, a CPI equal to 0 indicates an element that carries change, and a CPI > 0 indicates an element that multiplies change.

Lastly, some general findings are given based on insights provided during the research. These general findings can be retrieved from insights during interviews with suppliers, the concept development team, or the management team for example.

4 Results

4.1 Product Breakdown Structure

The first data that is collected is the data needed for the Product Breakdown Structure (PBS). The following PBS is composed in collaboration with the concept development team of MorgenWonen (see Figure 4-1). The housing concept with a width of 5.4m is chosen since this is the most developed and used concept of MorgenWonen.

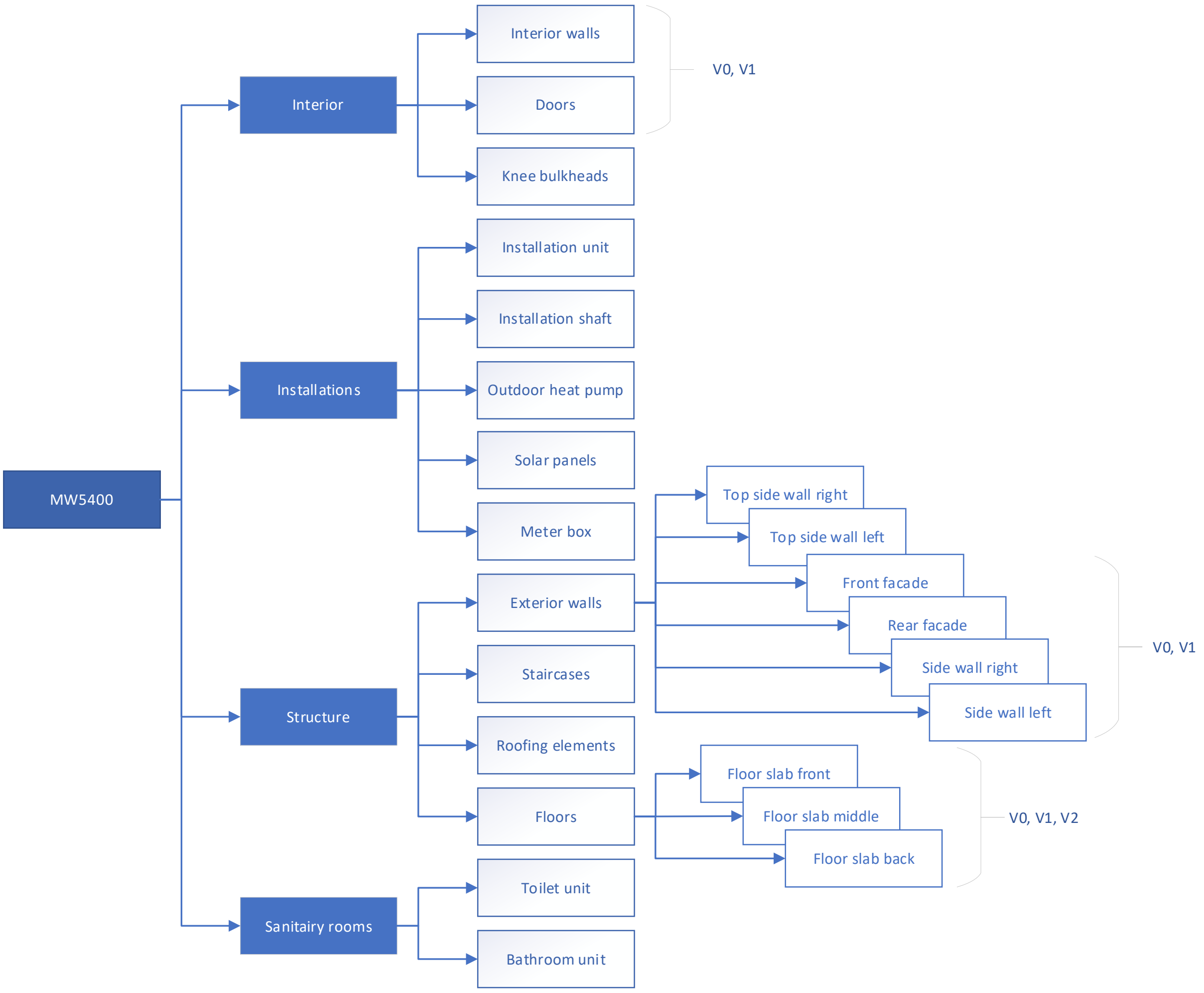

Figure 4-1, PBS of MorgenWonen 5400

This PBS defines the boundaries of what is called the conceptual design of MorgenWonen. Normally, one would also include the foundation and more interior aspects of the house in a PBS. However, this is not included in the concept of MorgenWonen. The foundation of the house is a prerequisite of MorgenWonen that must be present before the start of the assembly. Furthermore the interior aspects of the house, i.e. the kitchen, are excluded as well because this is not part of the product of MorgenWonen anymore. The PBS serves as input for determining the elements considered for impact analysis. Some elements may be combined or separated into different floors for the sake of the analysis. An exploded view of the considered elements can be seen in Figure 4-2 on the next page.

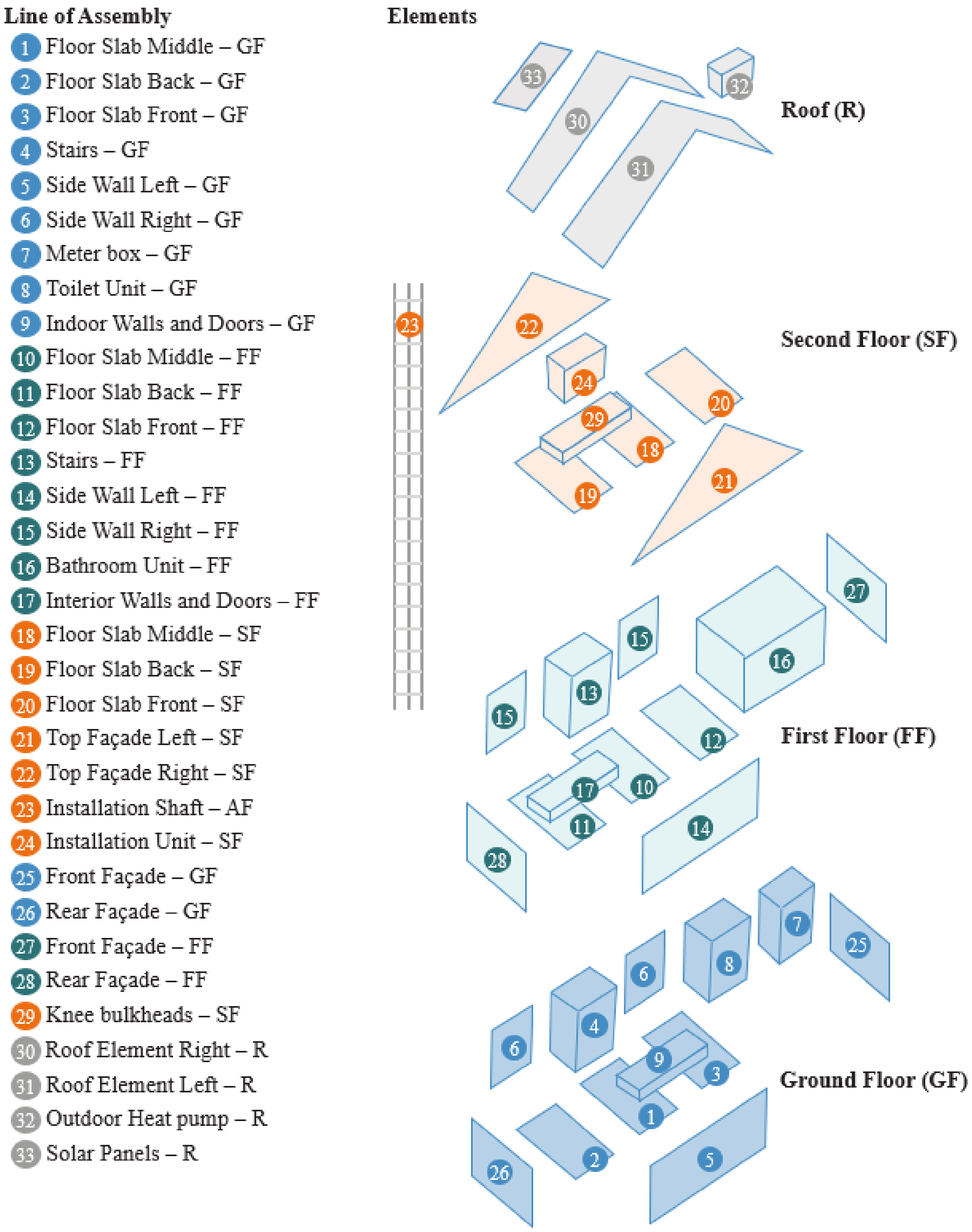

Figure 4-2, Exploded view of building elements

4.2 Technical Design Structure Matrix

The technical DSM is composed for the 33 elements as described above. An overview of the conceptual model to come to the DSM, graph the dependencies and quantify the impact is described in Figure 4-3. The main input for the model is an Excel file, which can be altered and expanded by the concept development team of MorgenWonen for future use. An overview of this Excel file can be found in Appendix A. Next the model creates CSV files which serve as the input for the software of Ratio-case, which transforms the CSV files into a readable DSM. The DSM can then be used to quantify the impact of each element on the whole design, and to graph the technical dependencies of any chosen element that is changed within the design.

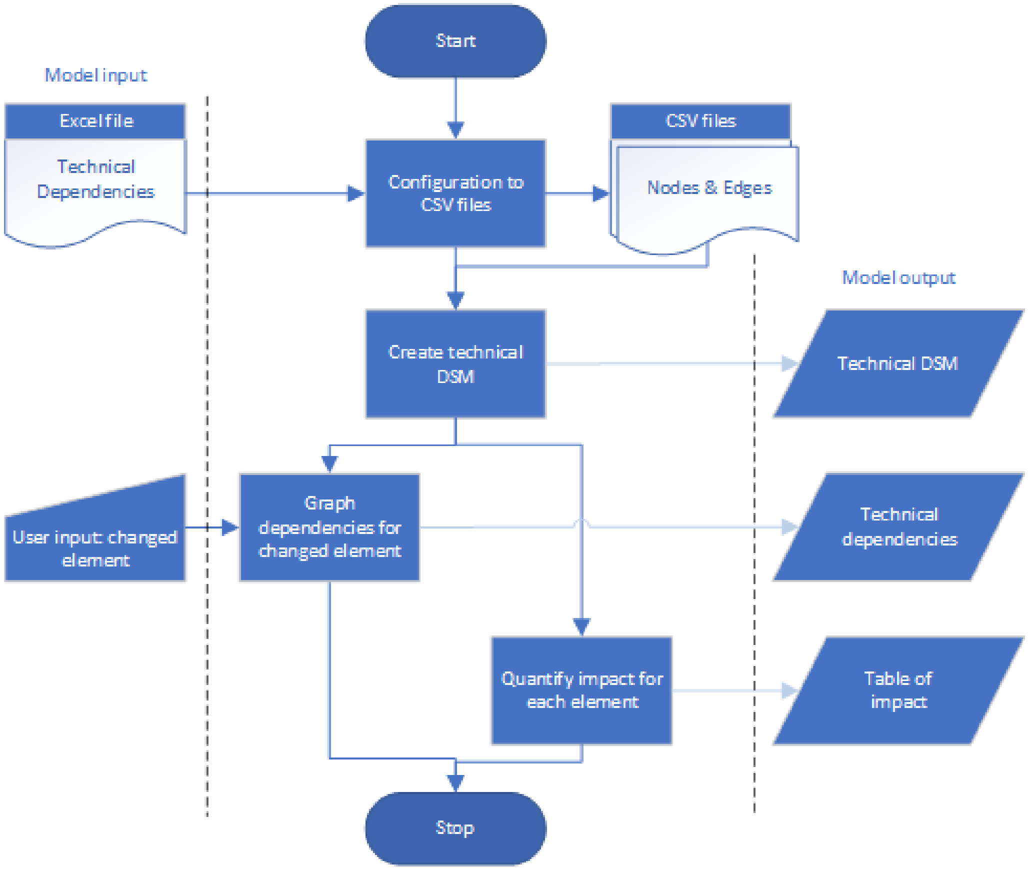

Figure 4-3, Conceptual flow diagram for technical dependencies

The data in the initial Excel file is gathered by meetings with experts, i.e. team members from the concept development team of MorgenWonen. During this meeting every possible combination of elements is considered and checked for possible dependencies. To make sure that the dependencies are mapped consistently a manual is used in which the rules for filling in the technical dependencies are described. This manual can be found in Appendix B (Dutch).

The dependencies within the model are constraint to the three different types of direct dependencies in this research. This could lead to missing certain change propagation paths. For example, changing the height of the facades and side walls would logically imply that the stairs unit must be heightened as well. However, this spatial dependency is not indicated in the matrix, since these indirect dependencies could possibly fill the entire matrix with possible dependencies. For the sake of clarity and analyses only the direct dependencies are indicated in the DSM.

The validation of the data is done to ensure quality and consistency. The technical dependencies are checked for symmetry where it is expected as described in section 3.1.1. This method of validation ensures that missing dependencies are filled in. Furthermore, all the dependencies are cross referenced with the (3D) technical drawings to ensure that the indicated dependencies are actually there. Furthermore, some dependencies are checked for common sense, i.e. the interior walls and the stairs unit are spatially interdependent, since the interior walls cover the stairs unit. However, in reality the stairs will never be redesigned in order to fit the wooden plates of the interior walls, but only the other way around. These ways of data validation ensure that both missing and existing data are validated. The validation of the data has caused an alteration of eighteen data points; eight through the check for symmetry, seven by checking for common sense, and three based on technical drawings.

The model gives three different outputs as indicated in Figure 4-3. These outputs are shown in the next figures with accompanying explanations.

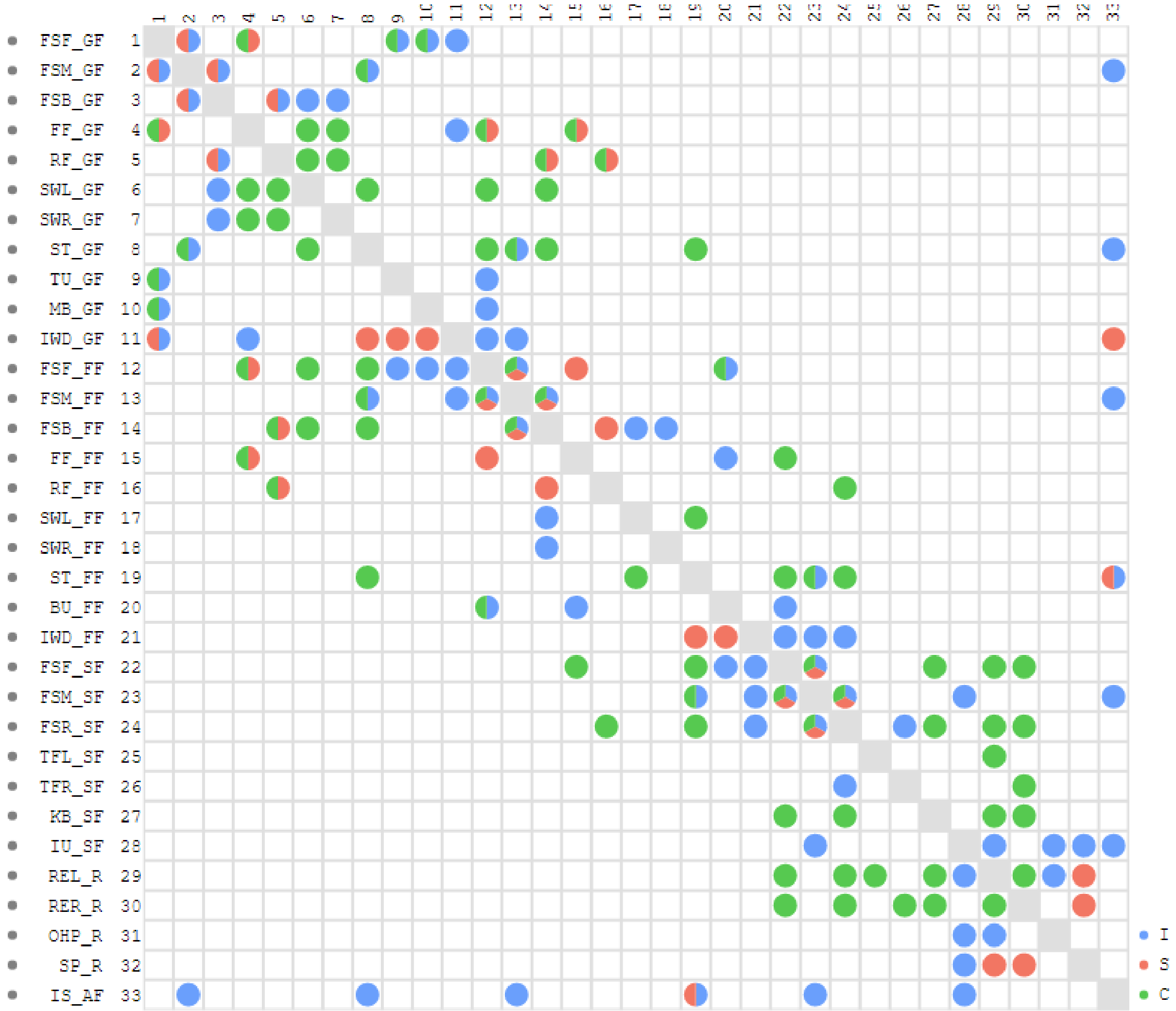

Figure 4-4, Technical DSM

Figure 4-4 shows the technical dependencies within the MorgenWonen – 5400 housing concept. The installation (I), spatial (S), and constructive (C) dependencies are given. The matrix should be interpreted as follows. Reading across a row indicates that that specific element has a dependency on the elements with an entry in that row (I, S, or C). A close-up of possible propagation paths starting at element 1 'Floor Slab Front – Ground Floor' can be seen in Figure 4-5 on the next page. In this example, all the elements that are dependent on element 1 actually cause a propagation of change to the dependent element (2, 4, and 9). In practice this is not always the case. It depends on the type and level of change whether or not a change propagates to a dependent element. Furthermore, the matrix looks symmetric along the main diagonal. However, this is not completely true. For installation and constructive dependencies the matrix should be symmetrical, since these connections go both ways. However, for the spatial dependencies this is not the case. For instance, inside walls are spatially dependent on other elements, but not the other way around, since concrete elements will never be spatially adapted to fit with the indoor walls. This is theoretically possible, but will never happen in practice. Therefore, the spatial dependencies are not completely symmetrical across the main diagonal.

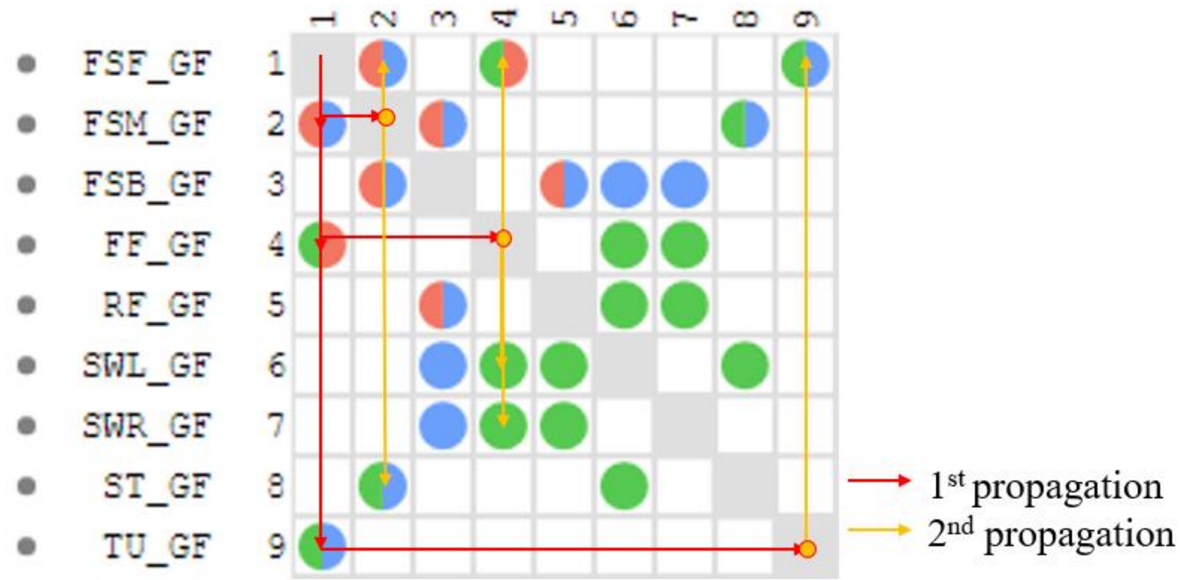

Figure 4-5, Possible propagation paths for element 1

The elements which are dependent on a certain element are also graphed by the model to give insights in the quantity of affected elements. Figure 4-6 shows the dependent elements of the stairs unit on the ground floor. These are all the elements that have an entry (I, S, or C) in column 8 of Figure 4-4. The type of dependency is indicated by an I, S, or C, or a combination of them.

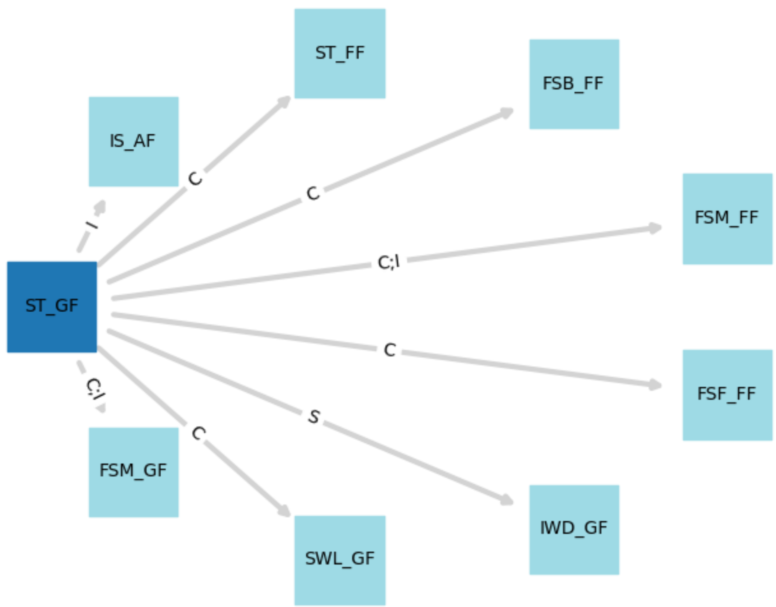

Figure 4-6, Dependent elements of the stairs unit ground floor

4.3 Supplier Domain Mapping Matrix

The supplier domain mapping matrix is composed together with the concept development team of MorgenWonen. An overview of the direct suppliers and their supplied products is given in Figure 4-7.

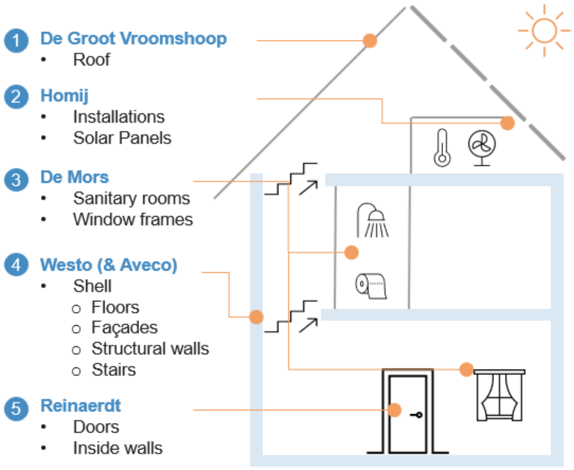

Figure 4-7, Direct suppliers of MorgenWonen

Next the responsibilities of the supplier must be mapped. Therefore, a supplier-DMM is composed. It shows which suppliers are responsible for which elements, either for production (P), engineering (E), or supplying parts (S), or a combination of them. Aveco de Bondt is considered in this DMM, since they are responsible for the engineering part of the concrete elements and are factually a supplier to MorgenWonen. However, they have close contact with Westo during the actual engineering processes.

The model input is an Excel file in which the responsibilities of all suppliers can be mapped. Figure 4-8 shows the conceptual flow diagram of the model. The model makes CSV files from the input-Excel to eventually make a supplier DMM with the help of the software of Ratio. This output can be found in Figure 4-9.

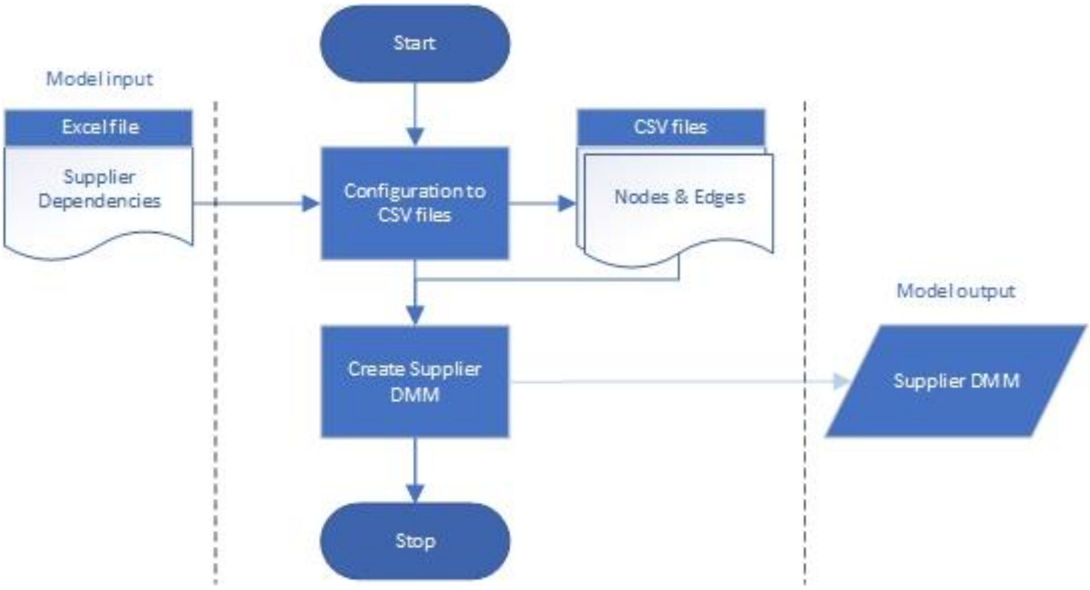

Figure 4-8, Conceptual flow diagram for supplier dependencies

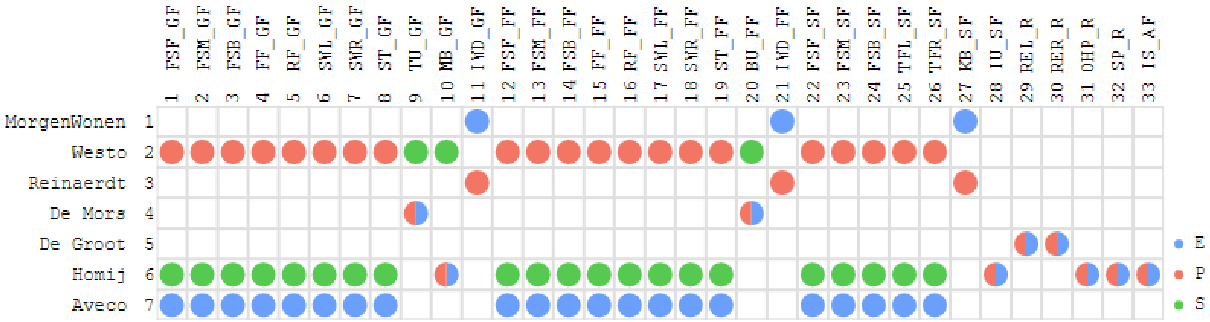

Figure 4-9, Supplier DMM

4.4 Process; Engineering hours and Lead times

The processes of re-engineering certain elements are considered to assess the impact of lead time and amount of engineering hours of engineering changes. In this paragraph both the engineering hours and lead times are discussed.

The lead times and engineering hours of either small, medium or large engineering changes are determined for each supplier through the semi-structured interviews. The minutes of these interviews can be found in Appendix C. An overall summary is given in this paragraph. For each supplier, examples of small medium or large engineering changes are given in such a way that they are comprehensive for that level of change. These changes can be found in Table 4-1 on the next page. Due to the comprehensive nature of the proposed engineering changes the concept development team is able to scale other types of changes to one of these proposed engineering changes when other impact analyses are done.

Table 4-1, Possible engineering changes with the direct suppliers

Supplier	**Small (*prep*)**	**Medium (*eng*)**	**Large (*purchase*)**
De Groot	Change location of recess (i.e. for heat pump connection)	Add a dormer to the standard design	Resize dimensions of the roof elements
De Mors	New interior design with current dimensions and connections	Relocate connection of sewage, cables and piping	Complete new design of bathroom and toilet unit including new dimensions
Westo	Relocate embeds in the concrete elements	Relocate or add recess in the concrete elements	Resize dimensions of the concrete elements
Reinaerdt	Add standard recess for sockets or other interior wall applications	Resize dimensions of interior walls	-
Homij	Replace content of installation unit with higher performing installations	Add prefab meter box to the design	Complete redesign of installation unit

The data retrieved from the interviews can be seen in Table 4-2. The lead times are given in the amount of days that it actually takes to finish the re-engineering process. So, when an answer is given in weeks or in months the exact amount (instead of the working day equivalent) is used in the dataset. The engineering hours on the other hand are given in hours and based on an eight-hour workday and five-day workweek.

Table 4-2, Lead times and engineering hours at each supplier for the proposed changes

Supplier	Small		Medium		Large	
	lead time (d)	eng hours (h)	lead time (d)	eng hours (h)	lead time (d)	eng hours (h)
De Groot	1	~	1	2/3	60/90	12
De Mors	7	2	30	8	90/120	16
Westo	1	1/2	60/90	8	180	64
Reinaerdt	1	2	14	4	n.a.	n.a.
Homij	1	2	20	10	75	30

4.5 Test-case calibration

A calibration is carried out to fit the model data best to reality. Especially the lead times and engineering hours are based on indications of expert judgement at the supplier side. However, this might not give the best indication of the lead times and amount of engineering hours that will actually happen. Therefore, the model is calibrated to data of previous engineering changes. For this calibration the change of width in the front and rear façade are taken as initial engineering change for impact analysis.

The change will propagate through the design of housing concept, changing other elements which in their case can change other elements again. The technical impact of the engineering change is given by the amount of elements that change through the engineering change, while the commercial impact is given by the number of involved suppliers, amount of engineering hours and lead time of the total re-design. The model gives the following output:

- # elements changed: 19 elements
- # involved suppliers: 6 supplier
- # engineering hours: 117 hours
- Total process lead time: 194 days

According to the concept development team, the actual impact is slightly different. Through a semi-structured interview and data collected by e-mails and shared memory these four proxies should be as follows:

- # elements changed: 19 elements
- # involved suppliers: 6 suppliers
- # engineering hours: 160 hours
- Total process lead time: 152 days

It can be seen that the number of elements and involved suppliers are the same and correctly estimated by the model. However, the number of engineering hours and lead time slightly differ. The number of engineering hours is underestimated by roughly 25%. An explanation could be that the model focusses more on the actual engineering hours at the supplier side, rather than the coordinating hours within MorgenWonen, especially with such a big engineering change. Furthermore, the lead time of the total process is slightly overestimated by the model, again by roughly 25%. An explanation could be that the data in the model is based on the realistic expectations of the suppliers, while the data for this calibration fits a best-case scenario. So, changing the input of the model for the amount of engineering hours and lead time is not done since this change would seem a bit arbitrary and the output gives a good indication of the order of magnitude of the engineering change.

4.6 Technical and commercial impact

Now that the model is calibrated, the actual impact of expected engineering changes can be estimated through an impact analysis. This is done for three engineering changes differing in expected impact on the total design. What these changes actually entail can be found in the figures beneath (Figure 4-10, Figure 4-11, Figure 4-12).

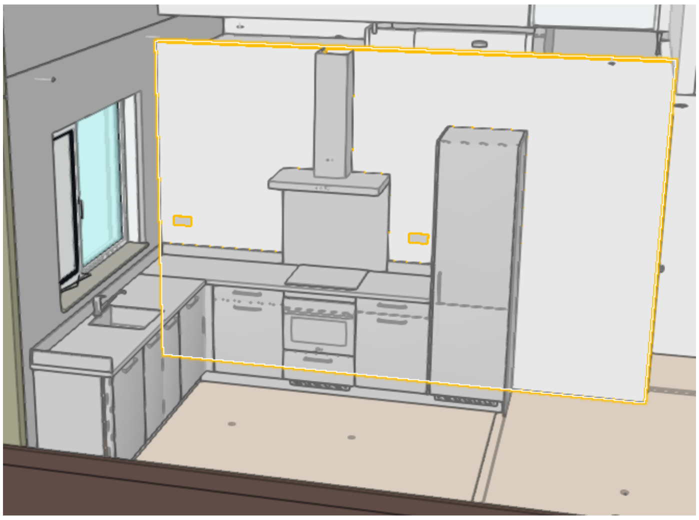

Figure 4-10, Standard recess in indoor walls

The recesses in interior walls are currently drilled at the construction site. This takes time and is most of the time inaccurate (i.e. they are not completely horizontal or the recess is made too big for the sockets). To avoid these inaccuracies and to speed up then process at the construction site, standard recesses can be added to the interior walls when they are at the factory. Reinaerdt is responsible for supplying the interior walls and have the machinery to add these recesses to the interior walls. However, production files and logistics should be taken into consideration to actually carry through this engineering change.

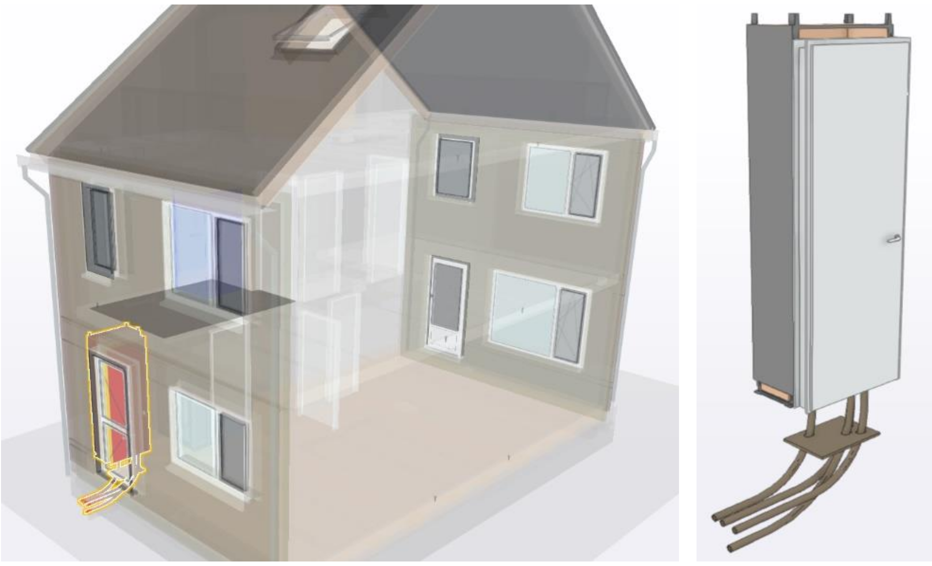

Figure 4-11, Pre-fab meter box

Utilities like water and electricity are currently installed by experts on the construction site. The exterior of the meter box is shaped with interior walls and doors and the contents are installed during construction. A pre-fabricated meter box should avoid this extra work on the construction site, with a more ‘plug and play’-kind of installation of utilities. The exterior and interior of the meter box are constructed in controlled environments which makes construction more efficient and accurate.

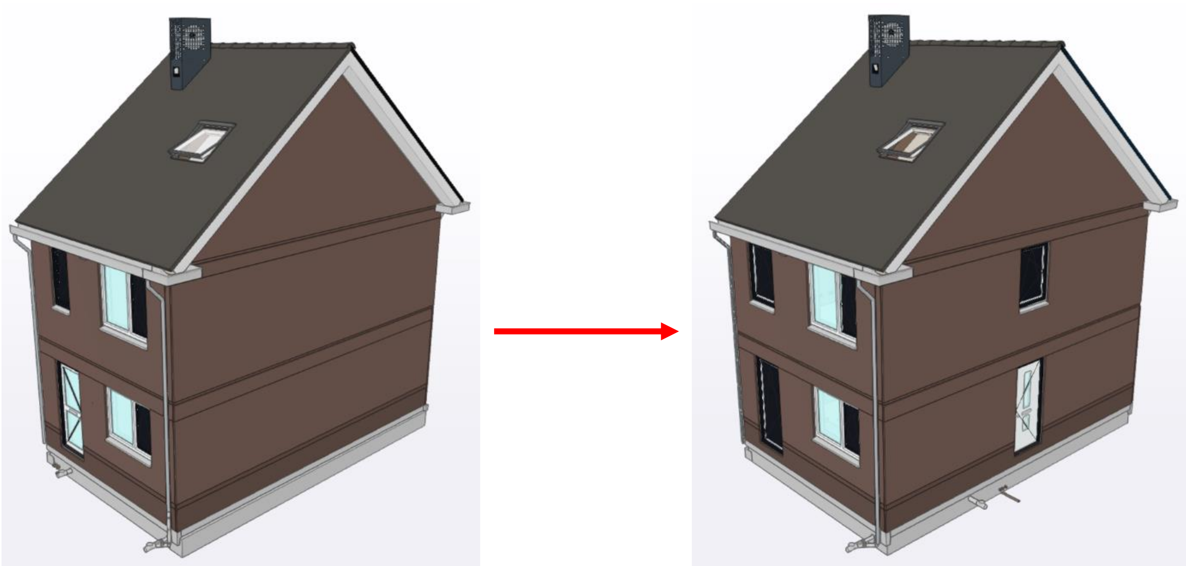

Figure 4-12, Change entry layout to sidewall

Lastly, one of the proposed engineering changes from the concept development roadmap which is used in this thesis is the change of entry layout. MorgenWonen wants to offer more options to buyers in their designs. Therefore, the engineering change of a side entrance is introduced. This option is possible for corner houses. Figure 4-12 shows two corner houses, the left one with a front entrance which is the current design for side housed, and the right one with a side entrance which is an option for the proposed engineering change.

4.6.1 Add standard recess in interior walls

Adding a standard recess to the indoor walls has a generally low impact. Since this engineering change is small and internal it will not propagate to other elements. Furthermore, the involved organisations only entail MorgenWonen for the engineering part and Reinaerdt for producing the indoor walls. The amount of engineering hours is 2 hours. The lead time for adding the standard recess in the interior walls is 15 days. So in short the impact of this engineering change is defined as follows:

- Technical impact: 1 affected element Low
- Commercial impact:
  - Involved suppliers: 2 involved suppliers Low
  - Engineering hours: 2 hours Low
  - Lead time: 15 days Low

The overall impact of the engineering change can be considered as low, which was also expected for this small and internal engineering change that does not propagate to other elements.

4.6.2 Add prefab meter box

The prefab meter box has a high impact on the design of MorgenWonen. While only three elements change, 5 suppliers are involved in the process. MorgenWonen, Westo, Reinaerdt, Homij and Aveco are involved in the process of designing the prefab meter box, since the meter box itself has to be designed, the floor slab on which it stands and the interior walls has to be redesigned. The amount of engineering hours in this design is 144 hours, and the process lead time is estimated at 194 days. In short the impact of this engineering change is defined as follows:

- Technical impact: 3 affected element Medium
- Commercial impact:
  - Involved suppliers: 5 involved suppliers High
  - Engineering hours: 144 hours High
  - Lead time: 194 days High

The overall impact of adding the prefab meter box to the design of MorgenWonen can be considered as high. The main reason for this is the commercial impact, including sourcing complexity, costs, and processing times.

4.6.3 Change entry layout from front façade to side wall

Changing the entry layout for a corner house has a medium impact on the whole design. While the number of affected elements is the largest (6), the involved suppliers are confined to MorgenWonen, Westo, Aveco and Reinaerdt. Furthermore, the amount of engineering hours is estimated at 50 and the total lead time of the redesign at 89. This lower lead time is especially caused by the medium engineering change in the concrete elements. Adding a (small) recess to the elements does not imply that new moulds have to be purchased. This significantly drops the lead time of the whole process. In short the impact of this engineering change is as follows:

- Technical impact: 7 affected element High
- Commercial impact:
  - Involved suppliers: 5 involved suppliers High
  - Engineering hours: 60 hours Medium
  - Lead time: 194 days High

The overall impact of this engineering change is estimated as medium, mainly due to the lower amount of engineering hours and shorter lead time than the previous engineering change. An overview of the model output of these engineering changes is given in the next paragraph.

4.6.4 Summary of technical and commercial impact

A summary of the technical and commercial impact of the above mentioned engineering changes is given in Table 4-3.

Table 4-3, summary of technical and commercial impact for the proposed engineering changes

	Technical	Commercial			Total impact
	#elements	#suppliers	eng. hours	lead time	
Recess indoor walls	1	2	2	15	Low
Prefab meter box	3	5	144	194	High
Entry layout	7	5	60	194	High

4.7 Validation

The validation of the model is carried out to check whether or not the output of the model reflects reality. Considering the three engineering changes it can be seen that the first engineering change (recess indoor walls) is completely validated by the concept development team. The team argues that the model output is in line with what is expected in reality. In other words, the amount of affected elements, involved suppliers, estimates of engineering hours and lead time are in line with their expectations

The second engineering change (prefab meter box) is partially validated by the concept development team. It was noted that the affected elements were in line with the expectations of the team. However, while developing the prefab meter box a new organisation came into the process. This means that new suppliers dependencies arise. So the supplier-DMM is not static but dynamic in this case. Therefore, it is hard to estimate the actual amount of engineering hours and processing time of the engineering change.

The last engineering change, changing the entry layout of the house, gives incomplete insight in the technical and commercial impact of the engineering change. The problem lies with the amount of changes in the design. Initially only the front façade and side wall on the ground floor change due to removing and adding a recess. The model shows change propagation to other elements (Floor slabs front and middle at the ground and first floor, and interior walls), however the reason for these propagations are not accurate. I.e. the change propagates to the floor slab in the middle on the ground floor due to the fact that the toilet unit and meter box are relocated on top of this element (actual), and not due to any spatial or installation technical dependency between the floor slab at the front and in the middle (model). The actual reason for the change propagation also inflicts new dependencies in the concept, since the floor slab in the middle is now dependent on the toilet unit and meter box. This means that the model is not static but dynamic, and that this engineering change propagation cannot be fully captured by the static DSM model as shown in this thesis.

4.8 General Analysis

The general analysis includes three parts; a cluster analysis, propagation analysis and general rules for redesign.

4.8.1 Cluster analysis

The cluster analysis is carried out with the algorithm of Ratio-case, based on the Markov Cluster Algorithm. It gives the following output when it is applied to the complete DSM (Figure 4-13)

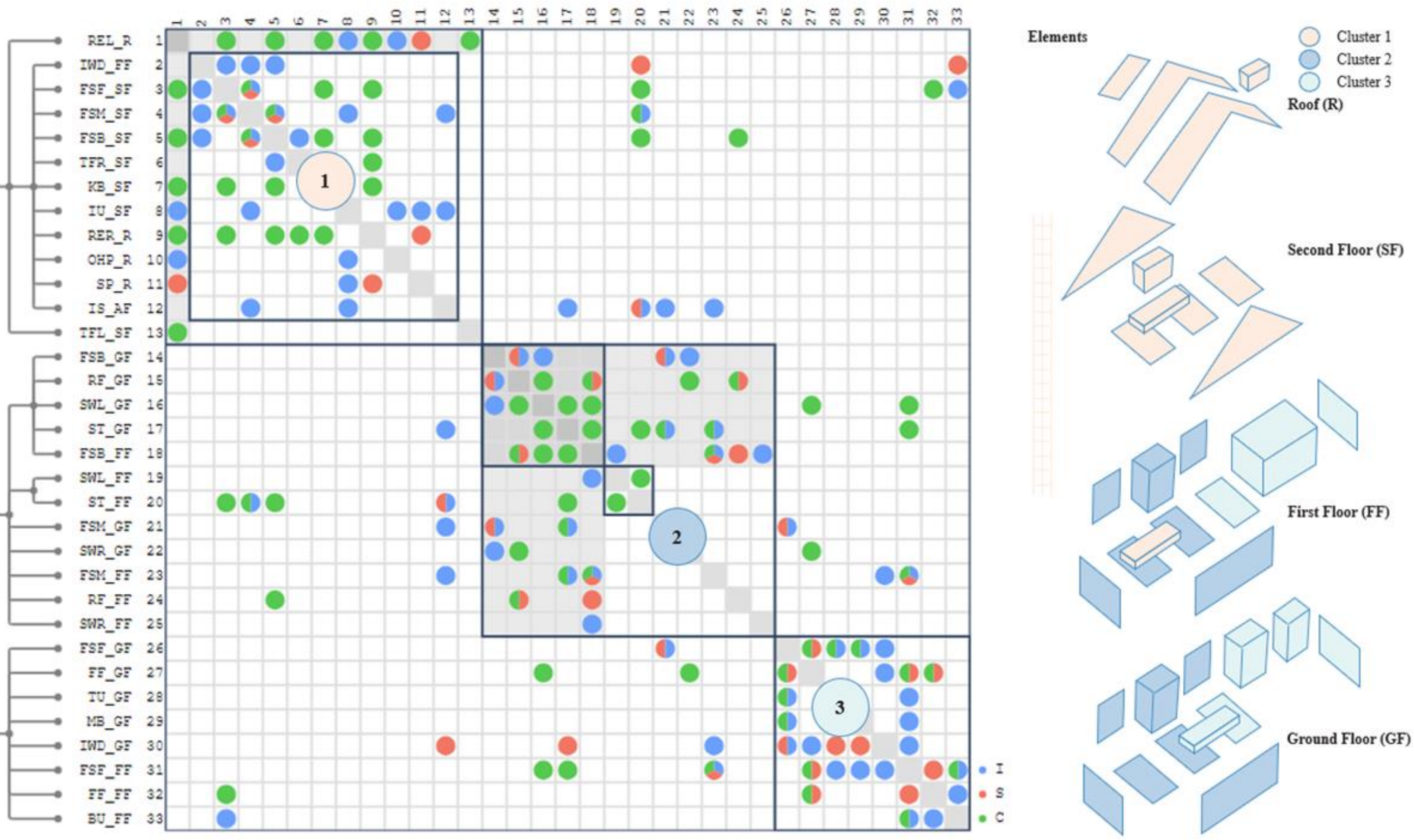

Figure 4-13, Technical DSM after cluster analysis and its exploded view

It can be seen that the first cluster is focussed on the elements on the second floor and roof, while the second and third cluster divide the ground floor and first floor into the front and rear part of the house. It can also be seen that the connections which are outside of the three clusters are not specifically for one type of element. The installation shaft, stairs units, floor slabs, interior walls, and bathroom unit all have some dependencies outside the identified clusters. Clustering the DSM based on the three types of dependencies individually do not give completely different clusters as can be seen in Appendix 10.4.

4.8.2 Propagation analysis

The propagation analysis is carried out to identify absorbers, carriers, and multipliers of change. The analysis is based on Equation (1) as described in chapter 3.7. This equation gives the output as can be seen in Table 4-4 on the next page. A value of zero means that an element has equal dependencies on other elements as elements that it is affecting ($\Delta E_{in} = \Delta E_{out}$). A value higher than zero means that the element is affecting more elements than that it is dependent on. A value lower than zero means that the element is dependent on more elements than that it is affecting. A completely symmetric DSM would show all 0-values in this analysis. The maximum value of 1 in the table is merely a coincidence.

Table 4-4, Change Propagation Index for all elements

Element	CPI	Element	CPI
Toilet unit GF	1	Side wall left FF	0
Stairs GF	1	Side wall right FF	0
Meter box GF	1	Floor slab middle GF	0
Stairs FF	1	Rear façade FF	0
Bathroom unit FF	1	Front façade FF	0
Roof element left R	0	Floor slab back FF	0
Installation unit SF	0	Floor slab middle FF	0
Roof element right R	0	Floor slab front FF	0
Outdoor heat pump R	0	Side wall right GF	0
Solar panels R	0	Side wall left GF	0
Knee bulkheads SF	0	Rear façade GF	0
Top façade right SF	0	Front façade GF	0
Top façade left SF	0	Floor slab back GF	0
Floor slab back SF	0	Installation shaft AF	0
Floor slab middle SF	0	Interior walls and doors FF	-1
Floor slab front SF	0	Interior walls and doors GF	-4
Floor slab front GF	0		

Table 4-4 shows that the interior walls and doors can be defined as absorbers of change. These elements are dependent on other elements for certain installation technical or spatial connections. An explanation could be that in theory other elements might be dependent on the interior walls and doors, however in practice these elements will never cause the change in another element. As mentioned earlier, a concrete stair element will never be changed for a wooden indoor wall, which is practically a wooden plate. So these elements absorb change propagation, and will most likely not affect other elements.

Most of the concrete and installation technical elements however can be seen as change carriers. For instance, the roof elements mainly carry the change of installation technical elements (like the solar panels, outdoor heat pump and installation unit) to each other. It does not multiply or absorb and is therefore defined as a carrier. Furthermore, the floor slabs and exterior walls and façades are categorised as carriers. These elements have multiple dependencies, so changing them would have a huge impact. However, since they are also heavily dependent on other elements they are categorised as change carriers.

Lastly, the sanitary rooms, stairs units and pre-fab meter box are categorised as change multipliers. A change in one element due to one dependency can cause multiple other elements to change. In short, these elements have more elements that are dependent on them than the other way around and thus have the potential to multiply the change propagation path.

4.8.3 General rules for redesign

Some general rules for redesign which are important to note are described here. Considering all the analyses that are done during this research it stood out that the concrete structural elements and the installation technical elements drive the lead times to its maximum. Especially the concrete elements cause the lead times to go up to the maximum of half a year. Figure 4-14 shows how the lead times evolve for propagation paths where the engineering change is large, so the engineering change always propagates to the next dependent element, and so on. The figure shows that all propagation paths accrue to the maximum lead time of 194 days between the second and fourth elements. This lead time can only be accomplished by large engineering changes to the concrete elements (resize dimensions of the concrete elements) of the housing concept. Medium engineering changes to the concrete elements or large engineering changes to the installation technical elements (see Table 4-1 for more detail) accrue to a lead time of 89 days, which is already seen between the first and third elements in Figure 4-14. It can be concluded that the concrete and installation technical elements are responsible for determining the lead times in examining the propagation paths.

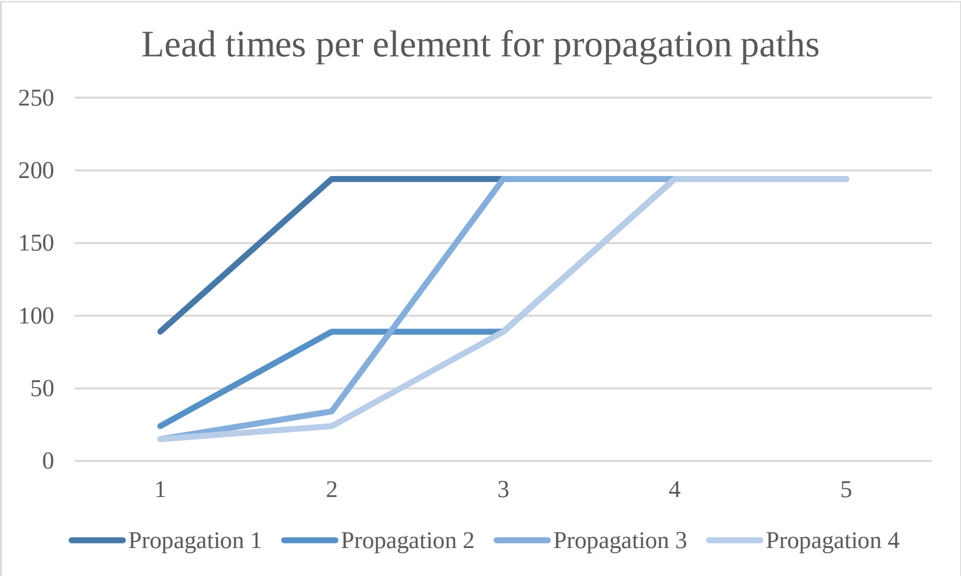

Figure 4-14, lead times with different propagation paths

Lastly, an important side note that echoed through this research during various interviews was information management. Everything can be done within considerable time frames when all the information is defined at the beginning of the project. All the suppliers mentioned that they could work a lot better when the right information is supplied to them at the right moment in the process. This is the key to optimally perform in the market and execute engineering changes continuously.

5 Discussion and Suggestions for Future Research

This research uses a Design Structure Matrix as main tool for impact analyses. The following limitation of using a DSM are described in this section. Firstly, the data that is needed to fill the DSM with dependencies must be valid and complete to come to good conclusions. Furthermore, a DSM is limited in its ability to capture the system's dynamics during an engineering change due to new dependencies or elements originating from the engineering change. Model-based systems engineering might be more applicable in this case. Besides that, the level of detail of each element can also influence the outcomes of the analyses heavily. Lastly, parametric design, which is a subject of discussion in the industrialised housebuilding industry, is far from practice. While scholars describe all kinds of possibilities for parametric design, practice is not yet ready to adopt it.

The first point of discussion of this research is the retrieved data from the company. The data for the DSM, the interdependencies between the building elements, is retrieved during discussion sessions about the housing concept with the concept development and work preparation team. However, it might be that these discussion sessions did not capture all the dependencies within the housing concept of MorgenWonen, since they are only based on the knowledge of the employees of MorgenWonen and construction site visits of the author. Furthermore, it can be discussed whether the predetermined types of dependency capture the whole dynamics of the system. Although these types of dependencies originate from literature, they do not completely represent all dependencies within the housing concept. For instance, non-physical stability (i.e. torsion) dependencies or building decree dependencies (i.e. daylight calculations) are not captured in this DSM. These data are not available at MorgenWonen, and also really hard to retrieve in general. Therefore, it is suggested that further research is done to validate and verify the current data set and to extend the data set with new types of dependencies.

Secondly, using the DSM as main tool of analysis has some limitations. A DSM is a static matrix by nature. Using the DSM for engineering changes brought some problems, since some engineering changes changed the system's dynamics. Thus the use of a static DSM for a dynamic engineering change was not possible. The new dependencies that occur due to an engineering change cannot be incorporated in the analysis when using a static DSM. Therefore other alternatives can be used to complement the DSM (not replace, since it is still a helpful tool for insights in change management). For instance, model-based systems engineering (MBSE) is a tool that brings a lot of benefits. According to Friedenthal et al. (2007, p. 5) MBSE can be described as "the formalized application of modelling to support system requirements, design, analysis, verification and validation, beginning in the conceptual design phase and continuing throughout development and later life cycle phases.". Henderson and Salado (2021) found multiple benefits of MBSE in their literature review like: flexibility in design changes, changes automatically across all items, flexibility in design architectures, and better predict behaviour of the system. In this light, it is interesting to do further research in the possibilities of MBSE for MorgenWonen in particular and for IHC in general.

Lastly, parametric design is a highly discussed topic in IHC. Also during this research, multiple discussions about parametric design for MorgenWonen were held. During this research it became clear that the industry is not yet ready for computer-automated parametric design, since human intervention is still needed in the current design and engineering processes due to the complexity and interdependencies of the housing concepts. The model that is made in this research also needs human intervention to prevent the model from infinitely iterating through the DSM. Currently the industry does not have the technological knowledge and skill to apply fully automated parametric design, mainly because the data of the interdependencies and methods of integrating parametric design are little-known. While this research was not primarily concerned with parametric design, it still is suggested that further research can be done into the barriers of adopting parametric design in the industry, since it is a promising concept, but it fails to land within organisations.

6 Conclusions

The objective of this research is to create a model that is able to define the technical and commercial impact of an engineering change. It can be concluded that such a model is made and that several general conclusions can be drawn from this model. The following conclusions are described in this chapter: Firstly, the concrete elements mainly drive the lead times of the engineering changes. Once a concrete element is involved in the engineering change the lead times go up to the maximum. Secondly, from the general analysis is can be concluded that the housing concept of MorgenWonen can be divided in three cluster; second floor and roof, the front side of the ground floor and first floor, and the back side of the ground floor and first floor. Lastly, not all possible dependencies are captured in the DSM.

The first conclusion is that a change in a concrete element drives the lead time to its max. This is caused by the long engineering process of a new concrete element. The concrete elements are designed and engineered by multiple organisations. Westo is responsible for the design of the concrete elements, while Aveco de Bondt is doing the constructive calculations for each element. Not only the design and engineering processes take time. Purchasing new moulds for the production of the concrete elements also takes a long time. The combination of engineering complexity and the purchasing process cause the high lead times of changing a concrete element. Therefore, it can be concluded that working with concrete elements in the industrialised housing industry makes the concept less agile in comparison to for example wood products.

The second conclusion regards the cluster analysis. With the currently used dependencies among the elements three main clusters can be identified. One big cluster is found at the second floor and roof, one on the ground floor and first floor at the front of the house, and one at the back site of the house. It can be concluded that the changes made within these clusters have a low probability of propagating to another cluster. The outcomes of the three cases that are used in this research are in line with this conclusion. Where the first engineering change did not propagate at all, the second engineering change propagated only within its cluster. The last engineering change initiated in two clusters and also did not propagate to the other cluster. Therefore, it can be concluded that the focus of modularisation should be within the dependencies of the clusters, since engineering changes already have a low possibility of propagating to another cluster.

The last conclusion that can be made from this research is that not all possible dependencies are captured in the DSM. The DSM now only entails three types of dependencies. This is a simplification of reality, since a lot more dependencies exist. This conclusion can be drawn since it was noticed that the propagation paths seen in the analysis of the three cases were not always correct. The change propagated to the correct elements, however for the wrong types of dependencies. For example, a change can propagate through an installation technical dependency to another element, while in reality it only propagates through non-physical stability dependencies that are not captured by the DSM as mentioned in the discussion. The incompleteness of the DSM does not have large consequences for the results of the analysis, due to the interconnectedness of all the elements. In the three cases the change propagation path has led to all affected elements in the engineering change, even though it was through the wrong dependencies.

Taking together all conclusions and limitations of this research, it can be concluded that the use of a Design Structure Matrix and Domain Mapping Matrix is only helpful for giving insights in the dynamics of complex systems like houses. They are not fit for fully automated impact analysis, let alone parametric design. The results of the analysis can be used as guiding tool for concept development. The DSM and DMM's must be accompanied by other product architect and change management tools to gain more insights in the impact of engineering changes to the housing concepts of MorgenWonen.

7 Managerial Recommendations

Recommendations to the management of MorgenWonen are made to give new insights in the current methods and process. Four recommendations are given in this chapter. The first recommendation is to focus on modularisation of the building elements, since the DSM is already filled with a lot of dependencies. Secondly it is recommended that the processes of engineering changes are standardised, also for the direct suppliers of MorgenWonen. The third recommendation is to give MorgenWonen the role of a system's architect, to oversee all dependencies among elements, suppliers and process. Lastly it is recommended to document engineering changes better, building a dataset, and learning from past mistakes. Elaborations of these recommendations can be found below.

Modularising the elements of the MorgenWonen concept micht be an obvious statement, however it is still recommended. The DSM is filled with 203 different connections among 33 elements and not all possible elements are included in the DSM yet. This means that there are even more dependencies among the elements, making the system even more interconnected. Modularising the elements either lessens the dependencies among elements or will diminish the propagation of a change. A dependency can be diminished, for example, by combining two elements into one standardised module. Diminishing a propagation while keeping the dependency can be achieved by creating standard interfaces between highly dependent elements. In this research it came forward that the stairs units, sanitary rooms, and meter box are change multipliers and so it is recommended to focus on modularising these elements, and besides focus on elements and dependencies within the identified clusters, since change propagation is expected within these clusters.

Determining standardised and documented processes for engineering changes within MorgenWonen and among its suppliers is highly recommended. During this research it became clear that there are no standardised processes or methods used during engineering changes. MorgenWonen does have a concept development roadmap, however there are no defined tools or methods for change management. The absence of defined tools and methods for concept development was even more evident at the suppliers of MorgenWonen. Most of the time it was unclear how long the lead times for an engineering change were or how many hours are needed to perform certain tasks. Making standardised process and using predefined tools among MorgenWonen and its suppliers can give a lot more insights in the impact of an engineering change. For example, De Mors has a predefined planning scheme for their engineering work, indicating lead times of certain engineering tasks. When these type of insights are standardised for the whole supplier network it will become a lot easier to define the impact of an engineering change and optimise the process of concept development. Implementing these standardised processes among the suppliers is a unique opportunity since the organisation are all part of the VolkerWessels group.

MorgenWonen needs to act as system's architect. A system's architect sets the boundary conditions for all elements within a product and can therefore oversee all interfaces among those elements. To become a system's architect, the concept development team needs to possess certain skills and expertise. These skills are also recommended in the simultaneously written thesis of the same author (Burghouts, 2023, p. 30). Further details can be found in the referred report.

Lastly it is recommended to document data from engineering changes. Data about engineering changes that was needed for this research was often not documented. Documentation about engineering changes would have helped this research, but will also help the concept development team in continuously improving their processes. It is recommended that during each engineering change, the consequences, actions, engineering hours, lead time, and unexpected deviations are documented. In this way a dataset of the past engineering changes is built. The dataset can serve as input for analyses and possibilities for learning.

8 Scientific Contribution

First of all, this research shows how different components of conceptual housing designs interrelate with each other. In their study, Bulloch and Sullivan (2009), identify informational relationships between tasks in the real estate development process, using a Design Structure Matrix (DSM). Similar to this research, relationships in the design/development process are identified. However, the study of Bulloch and Sullivan (2009), focusses on the relation between informational tasks within the development *process* of one-time real estate projects. This study focusses on the relation or interdependencies of building *components* in the design of industrialised housing construction and thus applying a DSM from a totally different perspective.

Secondly, Veenstra et al. (2006) developed a product platform for an industrialised housing construction firm in the Netherlands. The focus of this research is to identify modules which should be standardised or modularised. They identify which components in the conceptual houses should be standardised due to their influence on other components, and which components must be modularised due to the way they are influenced by other components. This research does not focus on the standardisation or modularisation of building components, but rather identifies the impact of a certain change, and assess to what extend a static product architecture DSM is able to capture these changes.

Lastly, the importance of this research should be noted. According to Engel and Browning (2008), large scale engineering projects typically involve three features; they are long-lasting, exhibit economies of scale, and future requirements are highly uncertain. These three features apply perfectly to the industrialised housing industry, and stress the importance of a proper product architecture. A product architecture gives insight in the relations between components of the product, resulting in possibilities for long-lasting designs, economies of scale and especially for redesign if future requirements change.

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10 Appendices

10.1 Appendix A

↓ has influence on →

Floor	Element	Code	FSF_GF	FSM_GF	FSB_GF	FF_GF	RF_GF	SWL_GF	SWR_GF	ST_GF	TU_GF	MB_GF	IWD_GF	FSF_FF	FSM_FF	FSB_FF	FF_FF	RF_FF	SWL_FF	SWR_FF	ST_FF	BU_FF	IWD_FF	FSF_SF	FSM_SF	FSR_SF	TFL_SF	TFR_SF	KB_SF	IU_SF	REL_R	RER_R	OHP_R	SP_R	IS_AF
Ground Floor	Floor slab front	FSF_GF																																	
	Floor slab middle	FSM_GF																																	
	Floor slab back	FSB_GF																																	
	Front façade	FF_GF																																	
	Rear façade	RF_GF																																	
	Side wall left	SWL_GF																																	
	Side wall right	SWR_GF																																	
	Stairs	ST_GF																																	
	Toilet unit	TU_GF																																	
	Meter box	MB_GF																																	
	Interior walls and doors	IWD_GF																																	
First Floor	Floor slab front	FSF_FF																																	
	Floor slab middle	FSM_FF																																	
	Floor slab back	FSB_FF																																	
	Front façade	FF_FF																																	
	Rear façade	RF_FF																																	
	Side wall left	SWL_FF																																	
	Side wall right	SWR_FF																																	
	Stairs	ST_FF																																	
	Bathroom unit	BU_FF																																	
	Interior walls and doors	IWD_FF																																	
Second Floor	Floor slab front	FSF_SF																																	
	Floor slab middle	FSM_SF																																	
	Floor slab back	FSR_SF																																	
	Top façade left	TFL_SF																																	
	Top façade right	TFR_SF																																	
	Knee bulkheads	KB_SF																																	
	Installation unit	IU_SF																																	
Roof	Roof element left	REL_R																																	
	Roof element right	RER_R																																	
	Outdoor heat pump	OHP_R																																	
	Solar panels	SP_R																																	
All	Installation shaft	IS_AF																																	

10.2 Appendix B

Handleiding invullen DSM

- Afhankelijkheden invullen d.m.v. de letteraanduiding.
- Meerdere afhankelijkheden binnen één cel scheiden door ';'

- Vul een constructieve (C) afhankelijkheid in als:
  - Het wapeningsnet veranderd moet worden
  - Verbanden tussen elementen veranderd moeten worden
- Vul een Installatie (I) afhankelijkheid in als:
  - De locatie van de connectie tussen installaties verandert
  - De installaties binnen het element veranderen
- Vul een ruimtelijke (S) afhankelijkheid in als:
  - De afmetingen van een element veranderen
  - De locatie/oriëntatie van een element verandert

10.3 Appendix C

10.3.1 De Mors

Interview commercial dependencies De Mors 11-04-2023

Present:

- Isabel de Waard (interviewee)
- Koen Burghouts (interviewer)

Questions:

1. Which processes are gone through when an element is changed?
2. How long do these processes take?
3. How many engineering hours are calculated for redesign?
4. Which suppliers are involved in the redesign?

Scenarios:

- New interior design with current connections and dimensions
- Relocate connection of piping
- New dimensions for the bathroom/toilet unit

Actual answers:

1)

Planning op basis van deadlines en overdracht

- Terugrekenen vanaf eerste productie
    - Start productie
    - Machine bestanden gereed
    - Mock-up bouwen
    - Productie model gereed
    - Uiterlijke besteldatum
    - Engineering model → Afstemmen met opdrachtgever
    - Start tekenwerk

2)

Doorlooptijden

- Start productie (5 dagen)
- Machine bestanden gereed (5 dagen)
- Mock-up bouwen (20 dagen)
- Productie model gereed (20 dagen)
- Uiterlijke besteldatum (60 dagen)
- Engineering model → Afstemmen met opdrachtgever (65 dagen)
- Start tekenwerk (85 dagen)

Side note: Doorlooptijden zijn gebaseerd op verwachting van myCUBY, maar kunnen afwijken als opdrachtgevers/ leveranciers niet meewerken of communiceren

3)

Engineering uren zijn doorgerekend in de totaalprijs van de myCUBY elementen en worden eigenlijk nooit specifiek onder die post doorgerekend aan klanten. Bij MorgenWonen waarschijnlijk al helemaal niet omdat het binnen VolkerWessels valt.

4)

- Westo
- Homij
- Dyka
- Sanitair (verschillende leveranciers, technische unie, revital)
- Euramax (wandafwerking panelen)
- Kuiper (sandwich panelen)

Data to use for thesis (generalised and translated):

Processes and their leadtimes

- Engineering/Drawing (20 days)
- Coordination with client (5 days)
- Purchasing goods and model production (40 days)
- Production test (15 days)
- Start production (5 days)

Lead times are based on expectations from myCUBY, but could differ based on lack of clarity or communication by client or suppliers.

Engineering hours:

Are calculated within the total price of myCUBY elements and are never specifically calculated towards clients. Especially not for MorgenWonen since they are within the concern of VolkerWessels.

Suppliers:

Supplier	Product
Westo	Prefab floor element
Homij	Electrical installations
Technische Unie	Sanitary
Revital	Sanitary
Euramax	Aluminium wall cladding
Kuiper	Sandwich panels
Dyka	Piping and sewerage

10.3.2 Westo

Interview Westo 12-04-2023

Present:

- Geert-Jan Schutte (interviewee)
- Jelle van der Zwaag (support)
- Koen Burghouts (interviewer)

Questions:

5. Which processes are gone through when an element is changed?
6. How long do these processes take?
7. How many engineering hours are calculated for redesign?
8. Which suppliers are involved in the redesign?

Scenarios:

- Relocate embeds in the concrete elements
- Relocate or add recess in the concrete elements
- Complete new dimensions of the concrete elements

Answers:

1)

Westo is steeds meer betrokken bij werkvoorbereiding.

Processen die daarvoor doorlopen worden:

- Aangepaste productie tekening
  - Tekening worden uitgewerkt door pre-cast → contact via MW
- Evt wapeningstekening aanpassen
  - Wordt gedaan door Aveco
- Aanvullende bekistingen bestellen

Morgenwonen → aveco constructie → pre-cast tekening

Tegelijkertijd → Westo mallen bestellen

2)

Kleine wijziging:

We kunnen direct aan de slag bij kleine wijzigingen als het op tijd gemeld is. (0 uur)

Middelmatige wijziging:

Ombouwtijd van de mallen 0-3 dagen

Nieuwe sparing in gevel (2-3 maanden)

Grote wijziging:

IFC tekeningen aanleveren → doorlooptijd ligt aan hoeveel iteraties voor dit definitief is

Bestellen mallen (half jaar)

3)

Kleine wijziging:

Veranderen instortvoorziening → 1 tot 2 uur

Middelmatige wijziging

Sparing aanpassen → 1 werkdag

Grote wijziging

Andere dimensies:

- 2 dagen voortraject MW
- 2 dagen Interne voorbereiding
- 3 tot 4 dagen Aanpassen mallen productie

4)

Hendriks of Consmema voor de mallen

Ankertech of Leviat voor de magneten

Kraus, van Merkenstein voor de wapening

Homij voor vloerverwarming etc

Transcarbo voor kozijnen

Aanvullende punten:

- Belangrijkste punt is tijd → gegevens zsm definitief maken
- Prefab meterkast 5/6 weken tot het definitief bij Westo komt

10.3.3 De Groot Vroomshoop

Aanwezig:

- Gerrit Borkent (interviewee)
- Jelle van der Zwaag (support)
- Koen Burghouts (interviewer)

Vragen:

9. Welke processen worden doorlopen bij een ontwerpwijziging?
10. Hoe lang duren deze processen?
11. Hoeveel werkuren worden er ongeveer berekend hiervoor?
12. Welke toeleveranciers zijn betrokken?

Scenarios:

- Verplaatsen/verwijderen van b.v. een sparing voor warmtepomp
- Toevoegen van dakraam / dakkapel
- Verbreden van dakelementen

Antwoorden:

1)

Standaard processen zijn niet gedocumenteerd.

Proces bij bestelling van MorgenWonen is nu als volgt:

- We hebben een bibliotheek met de huidige standaard dakelementen waar we de benodigde elementen uithalen. Deze bibliotheek voorziet in 99% van de benodigde dakelementen voor een project. Heel sporadisch moet er door een aanvulling/wijziging iets aangevuld worden
- Bestelling naar interne houthandel voor bestellingen per project.
- Productie van de dakelementen

Bij kleine veranderingen, zoals b.v. het laten vervallen van een kleine sparing, is het een kwestie van intekenen en/of verwijderen. Dit engineering proces is verwaarloosbaar qua tijd.

Bij grotere veranderingen (grotere sparing voor dakraam o.i.d.) moet een constructeur er naar kijken. Echter is alles zo over gedimensioneerd dat de verandering vaak geen constructieve gevolgen heeft.

2)

Kleine wijziging:

Kleine sparing toevoegen of weghalen is verwaarloosbaar

Middelmatige wijziging:

Standaard dakkapel in nieuwe sparing (2 a 3 uur werkvoorbereiding)

Grote wijziging:

Complete herontwerp (paar weken)

Nieuwe afmetingen zonnepanelen (2/3 maanden doorlooptijd). (Overleg tussen MorgenWonen-HOMIJ-DGV en Fakro)

5,40 → 4,80 (anderhalve week werkvoorbereiding)

3) (daadwerkelijke uren besteed aan verandering)

Kleine sparing veranderen (nihil)

Sparing dakkapel herontwerp (2/3 uur)

Nieuwe afmetingen zonnepanel (2 weken)

5,40 → 4,80 (1,5 dag)

4)

Homij (pv panelen)

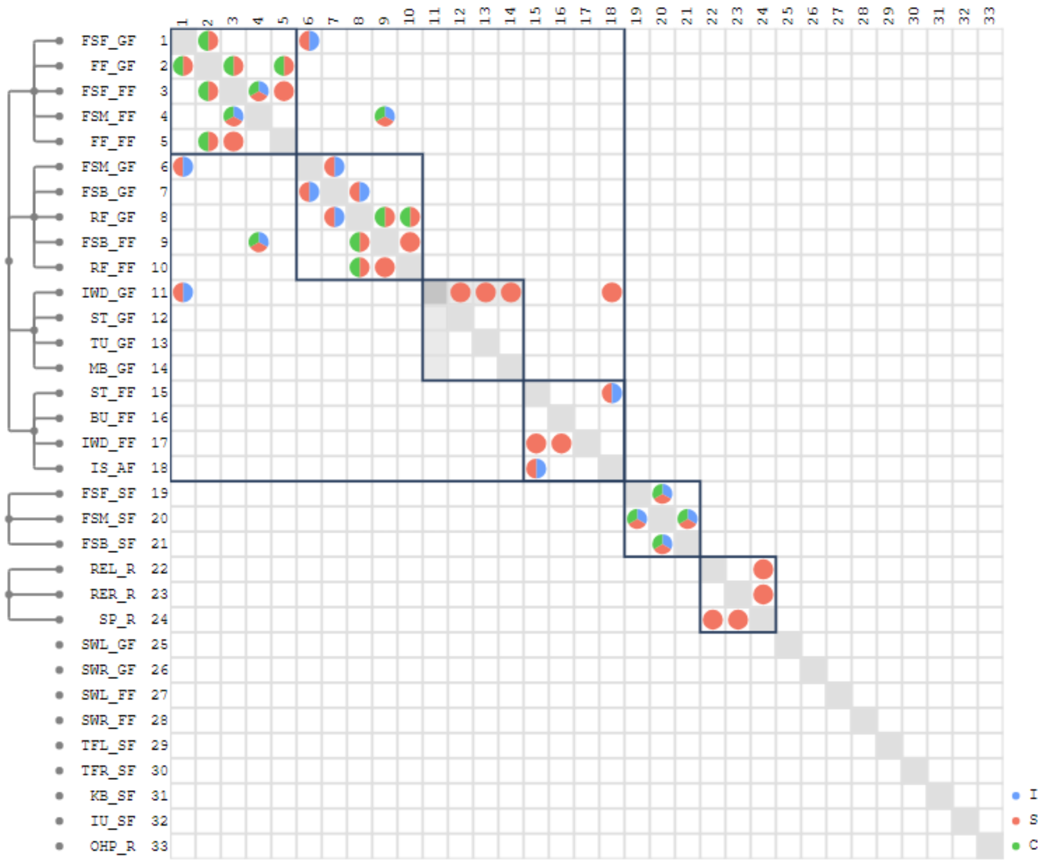
Comprifalt (Polyester boeien voor dakkapellen)

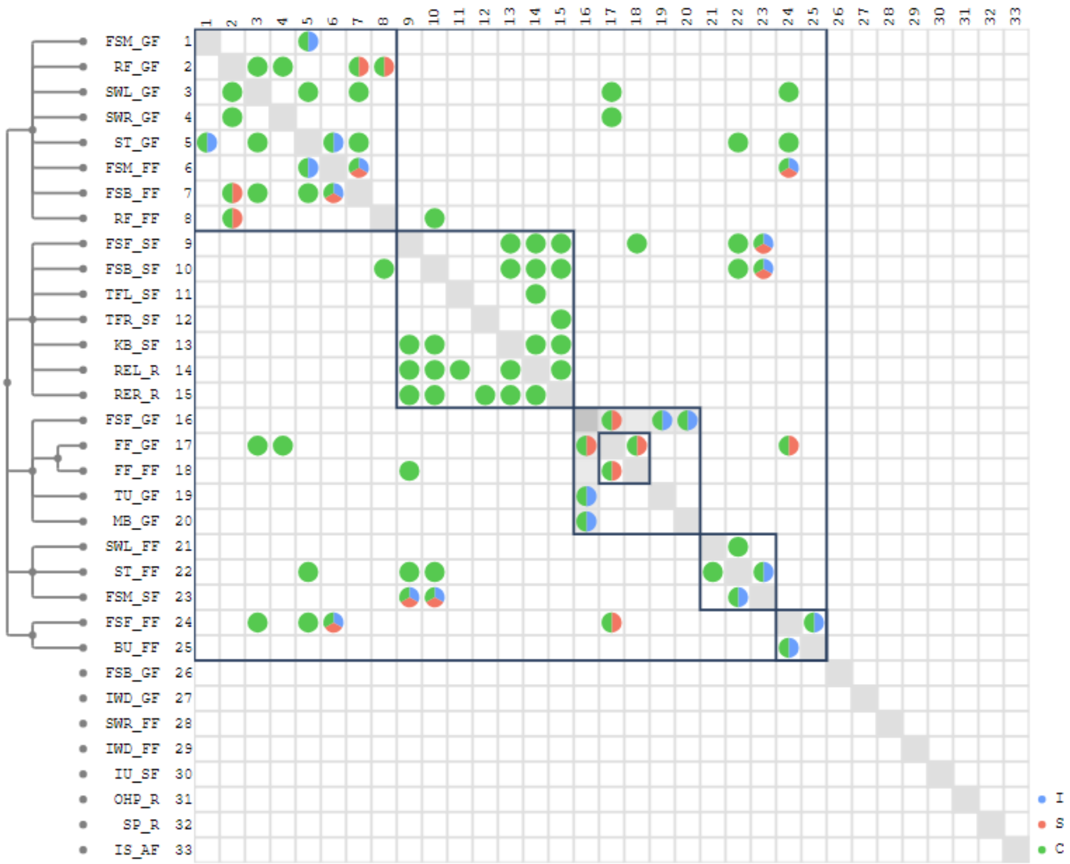
Raab Karcher (vensterbanken)

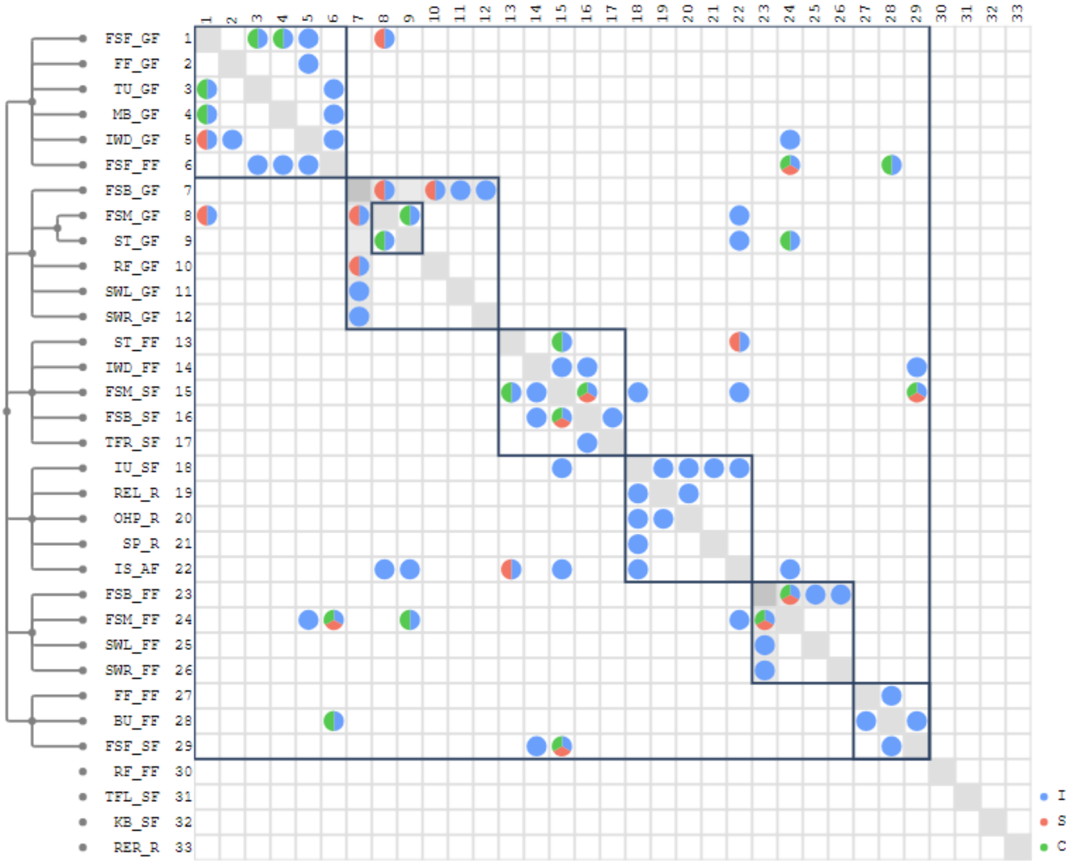
Interne houthandel (hout/ isolatie / folie)

MorgenWonen (levertijden van kozijnen van dakkapellen)

10.4 Appendix D



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KB_SF 32
RER_R 33
I
S
C