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VISUALISING THE IMPACT OF EARLY DESIGN DECISIONS ON A MODULAR HOUSING SUPPLY NETWORK

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ABSTRACT

Increasingly, modular housing manufacturers choose to compete by becoming system integrators. The transition to this new business model requires companies to develop system-level knowledge that 'they know more than they produce' in managing supply networks. Engineering system design tools, through visualizing supply network design and make processes, can help companies to overcome many uncertainties when they choose to become system integrators within the supply network. This paper illustrates how simulation models can be derived from design characteristics, experiential data, and a pragmatic system engineering design 'vee' framework. This helps modular housing managers to observe and compare the risks of different products and supply network configurations, and see how behavior changes of individual organizations impact system-level performance. A modular housing case study illustrates the implementation and benefits of our approach.

1 INTRODUCTION

In advanced economies, construction companies, including real-estate and infrastructure developers, are increasingly adopting mass customization models of production to improve construction processes (Bertram et al. 2019, Liu 2019). For example, in the UK, 40 % of home builders surveyed said that they were already investigating advanced manufacturing facilities for enhanced design capabilities, more product variety, and improved productivity (NHBC 2018). In Japan, off-site construction involving panelized and volumetric modules accounts for some 20 % of the million new single and multifamily homes built annually (Berg 2017). In Sweden, panelized construction has displaced conventional methods to the point where it now accounts for more than 80 % of all housing construction (Dodge 2020). In the context of humanitarian aid, off-site construction has significantly shortened the time to build emergency hospitals by enabling the construction of the foundation and the building envelope to take place in parallel (Ankel 2020).

Modular housing development is not a new construction concept. Modular housing developers use off-site construction through panelized and volumetric methods to reduce on-site construction cost and to enable earlier project completion time. Financially, this also delivers quicker returns for housing developers and reduces exposure to market cycle risks (Smith and Rupnik 2018, Bertram et al. 2019). There is a range of different procedures. For example, according to Burgess et al. (2018), using panelized construction, building structures are designed and manufactured off-site and then joined together on-site. In contrast, using volumetric construction, whole sections of buildings are manufactured through three dimensional modules and assembled off-site, and completed modules are then fitted together on the site.

Despite the many benefits of off-site construction (Smith and Tarr 2018), institutional norms and procurement practices within construction supply networks restrict effective collaborations between clients, modular housing system integrators (the prime construction contractor), and the wider network of sub-system, component, and material suppliers, as described in Burgess et al. (2018). This, in turn, restricts the potential value of adopting such methods. To realize the full productivity benefits of off-site construction methods, companies across the supply network require improved understanding of how the introduction of these methods influences supply chain operations.

In this paper, we introduce analyses, through discrete event simulation (DES), of how alternative design configurations of modular housing products influence supply chain operations. We use an application of a software tool initially designed for use in aerospace design-and-make supply networks (McKay et al. 2018). This allows the impact, in terms of supply chain risk, of early design decisions to be visualized early in a product development process. The tool exploits the fact that product architectures, which are fixed very early in the product development process and typically before supply chain factors have been considered, have a significant impact on the supply structure and, thus, on its operation. The simulation model generated uses this product architecture and supply options to construct the supply chain process logic. The tool comprises:

i) Data entry through a spreadsheet where the user defines a product architecture and associated make-or-buy scenario information typically available early in the product development process.
ii) Data are read from the spreadsheet into the WITNESS discrete event simulation package. Using pre-built designer modules that cover the different modes of process behavior, a model is automatically constructed and run. A series of runs is used to produce a delivery time risk profile for a given product architecture and make-or-buy scenario.
iii) Risk profiles for alternative product architectures and make-or-buy scenarios are compared.

In this paper, we begin, in Section 2, by introducing the method for transforming a product structure into a supply chain process using a systems design ‘vee’ model (McKay et al. 2018) that makes explicit the zig-zagging process of systems engineering, which iterates between and decomposes functional requirements, on the left-hand side of the vee, and solutions, on the right-had side of the vee. Details of the WITNESS interface software, including how design data are loaded, the simulation model built, and the results reported are provided in Section 3. Results from the application of the interface to a construction industry case study with modular housing are presented in Section 4. This includes the identification from a literature review of the types of supply network structures that occur in this sector and the definition of two scenarios applying different structures to modular housing. A discussion of potential challenges and opportunities for taking this work further is provided in Section 5.

2 METHOD

The research reported in this paper applies a software interface and tool that was developed for highly regulated industry sectors that design and develop large, complex, engineered products and where time overruns, often attributable to quality issues that arise during manufacture and operation, have substantial financial consequences. The overall architecture of the software, and so the method, is shown in Figure 1. We see that the software begins with a definition of a product breakdown structure and associated make-or-buy scenario. This information is entered into a software interface that, after processing, is translated into a WITNESS model where supply operations for the product and make-or-buy scenarios can be visualized. The first five steps are repeated multiple times, for different scenarios, and standard Excel functions were used to compare the supply chain operation implications of different product structures and make-or-buy scenarios. An alternative to this is to use the WITNESS Experimenter module to conduct the experimentation either through the interface or using the COM API.

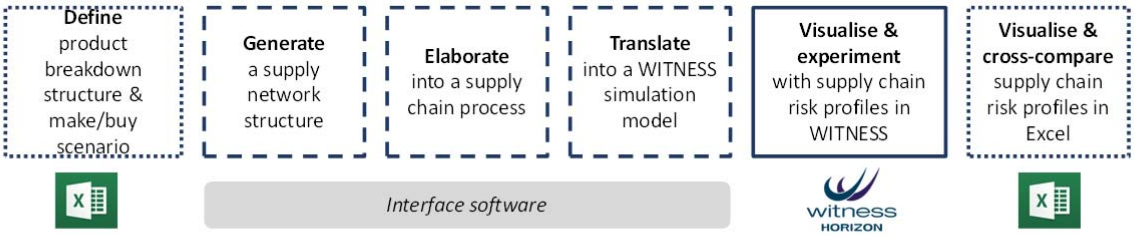

Figure 1: Overall software architecture.

2.1 Transforming a Product Structure into a Supply Chain Process

A product breakdown structure (in the form of an indented parts list) and the associated make-or-buy scenario drives the interface and so the resulting simulation models. The interface exploits key characteristics of a systems design vee (McKay et al. 2018) that expands on the traditional systems engineering vee model (Elliott and Deasley 2007) to make explicit the flow down of design requirements, on the left-hand side of the vee and the flow up of designs on the right-hand side of the vee. In the aerospace sector this results in a proposed design for certification. This design includes a product breakdown structure and, for each part in this structure, the outcome of a decision on whether the part is to be designed or made in-house or externally. With this information it is possible to generate a supply chain structure. An example of how make-or-buy decisions and product architectures affect the supply chain structure is shown in Figure 2, where, for clarity, only make-or-buy decisions regarding manufacture are shown. Three indented parts lists and make-or-buy scenarios are shown in the top half of the figure and corresponding supply chain structures are shown in the bottom half. We see that Part A is supplied by the prime contractor on Tier 0, shown in heavy outline, and the tiers below include suppliers of all bought parts. Where a part is made, these parts are made by the supplier on the tier above and this supplier also integrates these parts to form a whole sub-assembly. For example, in (a), the same Tier 1 organization makes F, sources D and E, and integrates them to form B; and in (b), the prime makes D, E, and F and integrates them directly with C to produce A without the need for a B. In this way, make-or-buy decisions and the product architecture have a direct impact on the supply chain's structure and composition. These supply chain structures are then used to produce a supply chain process structure by translating the nodes in the supply chain structure into process steps for a discrete event simulation model. The time taken for a given supply chain member depends on the number of parts they are making and integrating; default times are set in the Excel file, and these can be edited to reflect differences in time needed to make and integrate different parts. The same principles govern the design part of the process, and whether a given part is either designed in-house or externally.

The interface used in this paper was designed for aerospace supply networks where there is a strong regulatory environment and the chief engineer in the prime is responsible for the whole design, and so manufacturing, process. To capture this in the simulations, the vee model is applied twice to represent the operation of the supply chain: with the left-hand side of the vee representing the flow down of orders (a form of requirements) through the supply network and the flow up of supplied products on the right-hand side. To produce a simulation model, each of the boxes in Figure 3 is populated with a structure from that corresponds to the given product architecture and make-or-buy scenario.

In the simulation models, we introduce uncertainty into the model in two ways. Within process steps, the time taken to complete the step is subject to statistical variations available in WITNESS, and across the supply network we raise design queries that create rework and so iterations across process steps. Further details of these issues are provided in the next section and in a forthcoming publication. The interface discussed in this paper is a proof-of-concept prototype and was designed to enable the visualization of supply chain risk in the early stages of design, when product architectures are fixed and make-or-buy decisions made. Thus, the timing information is relative and based on practitioner experience. The data and results would need validating if the system would be used in earnest. However, we show that, given the same process times and likelihoods of rework, different product architectures and make-or-buy scenarios have a signifycant impact on the supply chain performance.

Part A			*Prime*
	Part B		*Buy*
		Part D	*Buy*
		Part E	*Buy*
		Part F	*Make*
	Part C		*Buy*

Part A		*Prime*
	Part C	*Buy*
	Part D	*Make*
	Part E	*Make*
	Part F	*Make*

Part A		*Prime*
	Part C	*Buy*
	Part D	*Buy*
	Part E	*Buy*
	Part F	*Buy*

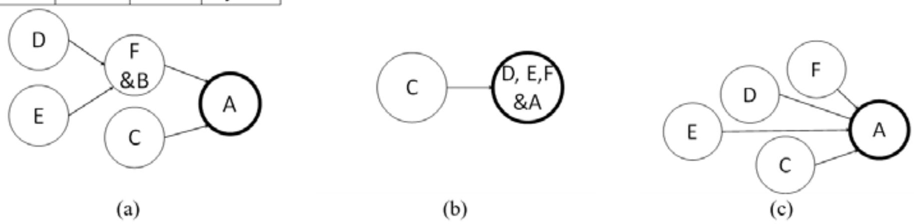

Figure 2: Product architectures, make-or-buy scenarios and supply chain structures.

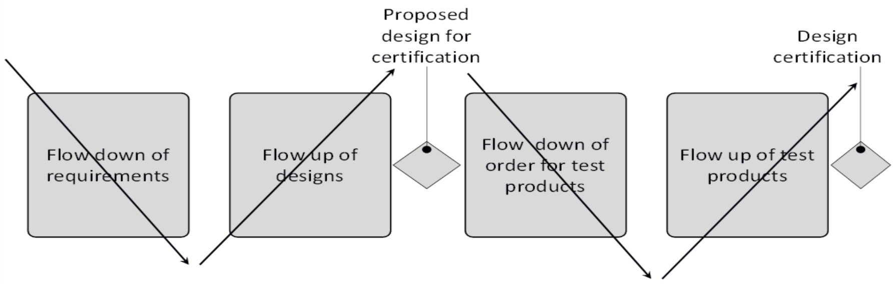

Figure 3: Double vee model.

2.2 The WITNESS Simulation Model Creation and Use

The data entered in the spreadsheet include the data shown in Figure 2, timing parameters for each step of the process generated and probabilities (as percentages) of the likelihoods of rework loops being needed. The model generated is a standard discrete event simulation (DES) model with simple flows of entities being directed by simple process logic. However, the creation of the model is interesting in that it is created automatically from the product structure data, i.e., the element structures within the model do not exist when WITNESS is opened, but are loaded from saved modules as indicated by the product architecture and make-or-buy scenario settings.

There are many ways to construct simulation models in WITNESS from the product interface to a full programming API. For this application, an intermediate method was chosen that uses the WITNESS Initialization actions to instantiate designer elements and load the appropriate modules. All data are loaded from Excel using data table elements and the initialization actions complete the job of linking up the modules and provide full control logic. An example of a design phase module is shown in Figure 4. This module actually contains 26 model elements. It includes several work phases and a generic logic to cope with design, verification, integration, system verification, and rework. The modules contain parameters such as timings and percentage flows that – when created – link to the data in the spreadsheet.

It is an increasing trend in simulation modeling to speed up model creation in this way, so that the technique can be applied to an increasing number of larger problems in an efficient manner. A more operational use of models for decision-making is also fueling the need for this. For many situations there is simply not the time to wait for lengthy simulation model creation. With this method, it is possible to move from data to results in minutes if not seconds.

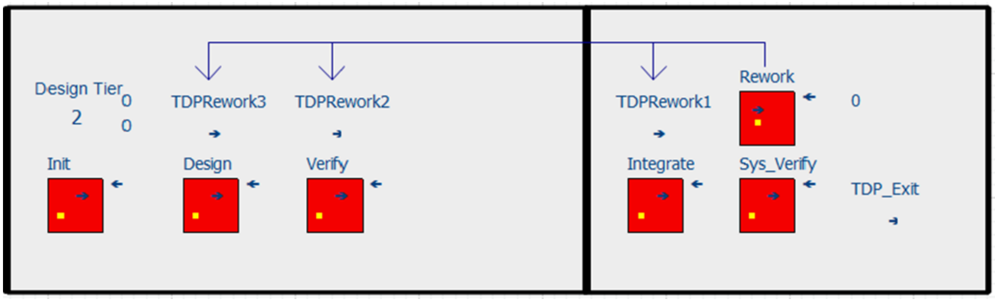

Figure 4: Example simulation module for a design phase.

Currently, the model is simplistic in that the timings are mainly deterministic and the activities do not share resources. Rework is sampled for based on percentages, and – of course – process entities must wait until full sets are present (e.g., in the verification of sub-assemblies). However, even at this simplistic level the software has shown promise in indicating comparative risk profiles for different scenarios.

With the variability that does exist in the model, the simulation for each scenario is run multiple times. This could be done in parallel, but for this paper it has been performed serially in a single simulation run. When one run completes, rather than rewinding the simulation, another set of work is loaded and the time continues. Only when all runs are completed the system does stop and output the key results on all runs back to Excel.

The model can be run from the spreadsheet or from within the WITNESS interface. A variety of report formats are created. Figure 5 is a chart produced inside WITNESS that shows the spread of times to completion of both the design, rework, and both together. The colors show this information for the whole design-and-make process (in blue), for the design process (in green), and the time taken in rework (in red). From the sequential runs described above, there are 46 different simulation replications shown for a single scenario on the histogram in this example chart. The x-axis shows the time taken and the y-axis shows how many replications took this amount of time. Charts like this are produced for each scenario and make it easy to compare the spread of predicted durations of the process for each.

3 APPLYING THE WITNESS INTERFACE TO A MODULAR HOUSING CASE STUDY

The system engineering vee is widely used in the high value manufacturing sector (see Section 2). However, little is known in applying it to modular housing supply chains. There are a number of product architecture similarities, but also some key differences. One such difference is the maturity of integration of such activities. For example, in modular housing development, architects and turnkey system integrators often have difficulties assessing the production capability in order to make holistic project scheduling decisions. However, modular houses are complex structures with different specialties in the design process and this similarity lends credence to the evaluation of the interface in this industry.

The information for the case study reported in this paper came from a leading UK modular housing system integrator (construction prime contractor). The focus was on the product breakdown structure and associated design-and-make decision-making process use to determine the modular housing system integrator's supply network. During the initial literature research stage, we adopted the established supply network framework (Wu and Choi 2005) to help identify existing literature regarding the indented part lists of modular housing supply networks for the proposed simulation interface tool (Section 2). Then, we verified the supply network configuration scenarios with the case company product configuration data, to ensure that they and the in-house or external supply options reflected the strategies of the case company. In Section 4, we apply the interface tool (Section 2) to the case study product breakdown structure to visualize risk profiles of the different supply network configurations for the modular housing case company. Beforehand, in this section, we review literature on modular housing supply networks (Section 3.1) and then introduce the modular housing case study in Section 3.2.

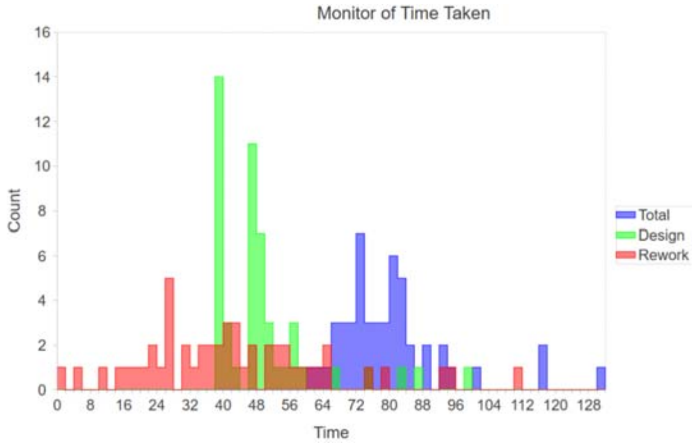

Figure 5: Timings (in simulation time units) for work completion.

3.1 Supply Network Configurations in the Modular Housing Sector

Scholars have studied systems engineering and supply network design across multiple industries (Randall and Ulrich 2001, Wu and Choi 2005, Hofman et al. 2009, Doran and Giannakis 2011). For example, building nuclear power plants requires extensive supply network design knowledge, including the selection of building materials, the layout of the reactor core, the choice of fuel types as well as coolant materials, and assessment of multiple subsystems capabilities (Metzler and Steinfeld 2014). In the computer industry, supply network design can be managed through loosely coupled subsystems, where the innovation speed of processors is greater than that for disk drives. Loosely coupled subsystems can help to reduce redesign effort each time new processors are introduced (Randall and Ulrich 2001). Given the importance of system quality, reliability, and safety in the aerospace industry, airframe manufacturing often requires component manufacturers to work together with cutting tool suppliers to provide detailed coordinated machining data for testing new components. This relieves the customer from the need to measure each of the components themselves (Spring and Araujo 2013). In modular housing development, system integrators or buyers define the functional specification, while the detailed engineering specifications can be left to the loosely coupled modular housing component suppliers. Similar to the computer processors and disk drives sector, the house components are often individually upgradeable since the interfaces are standardized (Hofman et al. 2009, Doran and Giannakis 2011).

Using established supply network frameworks (Wu and Choi 2005) different supply network configurations in modular housing development have been identified (see Figure 6):

i) Vertical supply network: sub-contractor network driven by the buyer.
ii) Lead supply network: multiple suppliers collaborate to share information and resources under one lead supplier.
iii) Collaborative supplier network: suppliers work together to meet the requirements of the customer (suppliers learn customer needs and market knowledge).
iv) Transactional supplier network: for the same buyer with little collaborative interaction.

In a vertical supply network (VSN) configuration, buyers often use preferred suppliers to produce non-integrated components that feature outsourced design and outsourced production. Sometimes buyers purposefully inject competition into the supply network to ensure that the sole sourcing status of the preferred supplier cannot be taken for granted (Wu and Choi 2005). Buyers also use direct sourcing from a preferred supplier and ask them to integrate other suppliers requested by the buyer. For example, Figure 6a shows that in the VSN supplier S1 is the preferred kitchen supplier and supplier S2 is the tiling supplier. The modular housing system integrator can ask S1 to buy from S2 and to co-ordinate the supplies.

In a lead supply network (LSN) configuration, the system integrator carries out the design for structural modules. Different components are manufactured and integrated externally, often from different sources. The intellectual property for the design and development of these modules is often owned by the integrator. The supply network potentially works collaboratively in close proximity, and might organize itself to defend from cost-cutting pressures of the integrator. For example, Figure 6b shows that the structural wall supplier S1 emerged as leader of the group and manages the design project, which also includes components from S2, S3, and S4. When the system integrator defines requirements, S1 will distribute these to the other suppliers and return collected technical data to the modular housing system integrator.

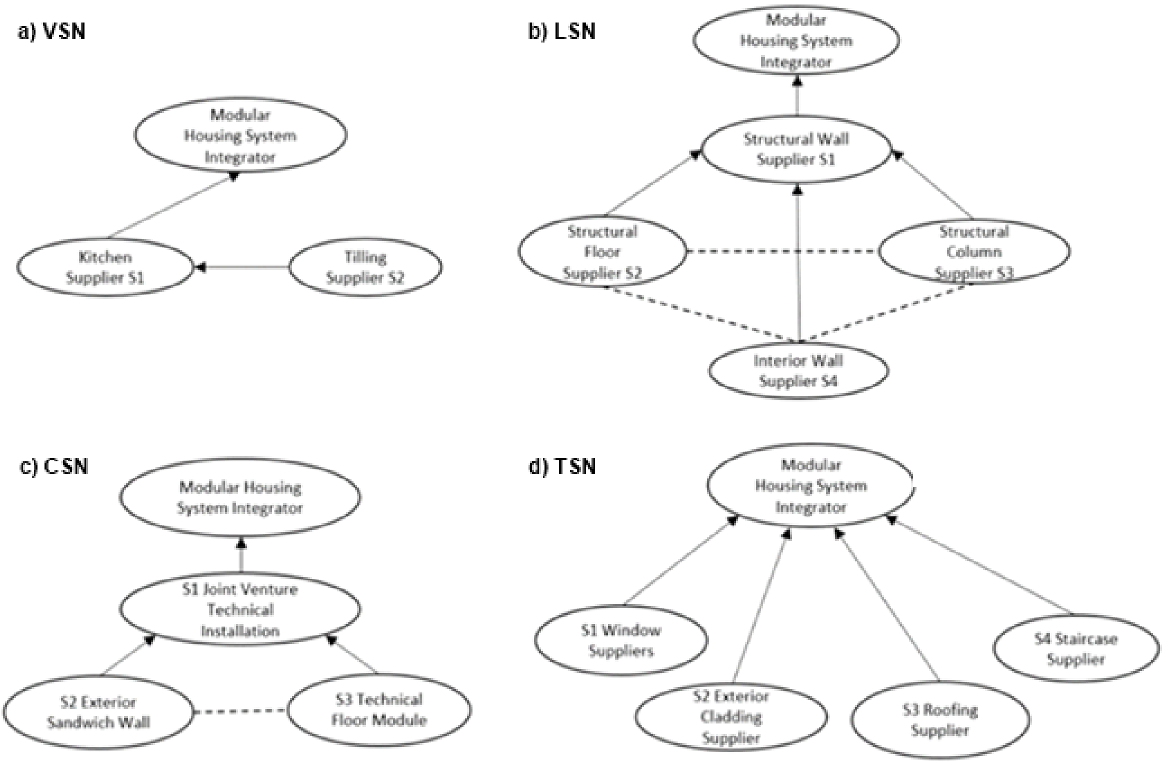

Figure 6: Supply network configuration options: (a) Vertical Supply Network (VSNI); (b) Lead Supply Network (LSN); (c) Collaborative Supply Network (CSN); (d) Transactional Supply Network (TSN).

In a collaborative supply network (CSN) configuration, the builder and manufacturers are increasingly integrating the roles of design, fabrication, and construction through a collaborative supplier network where suppliers work together to meet the requirements of the buyer, so that the supplier can learn customer needs and extends his market knowledge (Figure 6c). For example, CertainTeed, a leading materials manufacturer, partnered with Unity Homes to develop higher performance assemblies and components for factory-built housing (DODGE 2020). Japan has been considered as market leader in the modular housing development (Smith and Rupnik 2018). The recent success of Japanese modular housing export growth in Thailand and Australia has been widely reported (Berg 2017, Smith and Rupnik 2018, Bertram et al. 2019). Market leaders such as Seksiui Heim adopt Japanese Kieretsu style collaborative supply network relationships, where the 'Lead' firm fulfils the role of system integrator, and formulates cross-sharing holdings with the supply base (Yorozu and Shi 2014).

In addition, modular housing system integrators are potentially dependent on supplier expertise for the design and manufacturing of various modules. For example, a supplier of sandwich walls may have proprietary knowledge on material properties and production techniques to improve the overall modular housing design and manufacturability (Hofman et al. 2009). Input of supplier knowledge in this way often leads to improved designs. Indeed, in order to access proprietary knowledge that aids the overall module design, buyers can internalize design activities through joint design development with the supply networks.

In a transactional supply network (TSN) configuration, a modular housing system integrator can manage the supply network through keeping transactional suppliers away from each other (Wu and Choi 2005) for the benefit of buyer's efficiency and flexibility (Hofman et al. 2009). The supply structure is simple as shown in Figure 6d with virtually no communication between suppliers.

3.2 A Modular Housing Design-and-Make Case Study

A fundamental characteristic of the modular housing design-and-make process is the need to overlay plans onto predetermined product structure module templates in order to arrive at the most optimal solution (Doran and Giannakis 2011). According to McKay et al. (2018), acceptance for the next process stage at a stage gate can be used as a proxy for time risk in the design network. Thus, if a design is not accepted for the next stage in the process then time and cost are added to the overall network process for rework in an earlier stage of the process. Previous studies have identified motivations to internalize or outsource the design and make processes that the focal company chooses to position themselves within the supply network (Doran and Giannakis 2011, Baines and Shi 2015, Baines et al. 2017). For example, Seksiui Heim, a Japanese modular housing provider, uses internal design and outsourced make processes to increase variety and meet highly personalized clients' requirements. This allows the company to charge 8 % more than similar conventionally built houses (Smith and Rupnik 2018). According to Hofman et al. (2009) modular housing companies can choose to compete by becoming modular housing system integrators or modular suppliers that conform to the design rules laid down by turnkey system integrators.

We have verified supply network configuration scenarios found in literature with the procurement data shared by our specific case company to ensure that the proposed supply network configurations and parameters used reflect the supply network strategies of the case company.

Table 1 shows two potential scenarios of supply network configuration by the case company as a modular housing system integrator. Scenario 2 shows the potential opportunities of design integration between the case company and their potential strategic suppliers (VSN S2, LSN S4, CSN S1, and TSN S1, S3) for repeated system-level design capabilities. In contrast, Scenario 1 shows the case company potentially adopting more outsourced design and make in managing their supplier network. We identified three potential modular housing design-and-make strategic options: (1) internal design and internal make, (2) internal design and external make, and (3) external design and external make. The combination of external design and internal make options is not found within the case scenarios.

Table 2 shows an example of a table of input data. It includes input values used for the time taken for each stage of the process. The units are simulation time units (in this case days). The first ten rows are the times taken to complete specific activities in the design-and-make process. The final three parameters are the times needed to manage concessions that are raised. The final two columns indicate whether a given parameter relates to components, assemblies, or both. For example, the time needed to raise a concession request, P11, is the same for both assemblies and components, but, through P12 and P13, it is possible to define different amounts of time needed to review a concession for an assembly or a component. The timings shown and all other data feeding the simulation such as percentage of rework are experiential estimates through discussion with the company experts. The scenarios were each run for 500 replications to ensure the robustness of results. The simulation model focuses on the supply network design-and-make process of the off-site stage. Therefore, modular housing on-site construction time and logistical planning time are not considered in the simulation.

4 RESULTS

We applied the WITNESS interface (Section 2) to the supply network configurations (Section 3.2) to visualize risk profiles of alternative supply network configurations for the modular housing company. Our case study data focused on the flow down of requirements for a multi-family modular house, where the modular housing system integrator performs two key functions: (1) definition of interface specifications on how modules are physically connected, including structural loads and tolerances, and (2) translation of system-level requirements into sub-system requirements for different physical components of the modular housing. The system design flow up builds and verifies technical data packages (TDP) to ensure component sub-systems (such as structural wall, structural floor, and ceilings) fit together. Using the design and make options from Table 1, we illustrate two simplified process flows for a vertical supply network (VSN1 and VSN2). Figure 7 shows the VSN1 process flow with external design-make options for both S1 and S2. Figure 8 shows the VSN2 process flow with external design-make options for S1 and internal design and external make decisions for S2.

Table 1: Supply network design and make options in Scenario 1 and Scenario 2.

			Scenario 1		**Scenario 2**	
Modular Manufacturer as System Integrator			In-house	In-house	In-house	In-house
Part A	**VSN**		In-house	In-house	In-house	In-house
	Kitchen S1		External	External	External	External
		Tilling S2	External	External	**In-house**	External
Part B	**LSN**		In-house	In-house	In-house	In-house
	Structural Wall S1		External	External	External	External
		Structural Floor S2	External	External	External	External
		Structural Column S3	External	External	External	External
		Interior Wall S4	External	External	**In-house**	External
Part C	**CSN**		In-house	In-house	In-house	In-house
	Joint Tech Installation S1		External	External	**In-house**	External
		Exterior Sandwich Wall S2	External	External	External	External
		Technical floor S3	External	External	External	External
Part D	**TSN**		In-house	In-house	In-house	In-house
	Window S1		External	External	**In-house**	External
	Exterior Cladding S2		External	External	External	External
	Roofing S3		External	External	**In-house**	External
	Staircase S4		External	External	External	External

Table 2: Timings for the design-and-make process.

	Time Parameter List	Internal	External	Assembly	Component
1	Input Process	0.5	1	1	1
2	System Design Activity	0.67	0.67	1	0
3	Component Design Activity	1	1	0	1
4	Design Verify Activity	0.33	0.33	1	1
5	System Integration Activity	0.67	0.67	1	0
6	Output from a process	0.5	0.5	1	1
7	Make Activity	1	1	0	1
8	Make Verify Activity	0.33	0.33	0	1
9	Order Activity	0.33	0.33	1	1
10	Make Integration Activity	0.67	0.67	1	0
11	Concession Request	0.2	0.2	1	1
12	Concession Review Component	0.5	0.5	0	1
13	Concession Review Assembly	0.5	0.5	1	0

The scenarios in Table 1 were implemented in the WITNESS simulation package. The result charts in Figure 9 show significant delays if Scenario 2 is selected. Even at this simplistic level of modeling, this is a valuable input into quantifying project costs and durations through the visibility of such risk. The process maps created have also helped to provide clarity on flows. They are a concrete means by which managers can apply system engineering principles in the flow down of requirements and the verification and validation of design proposals.

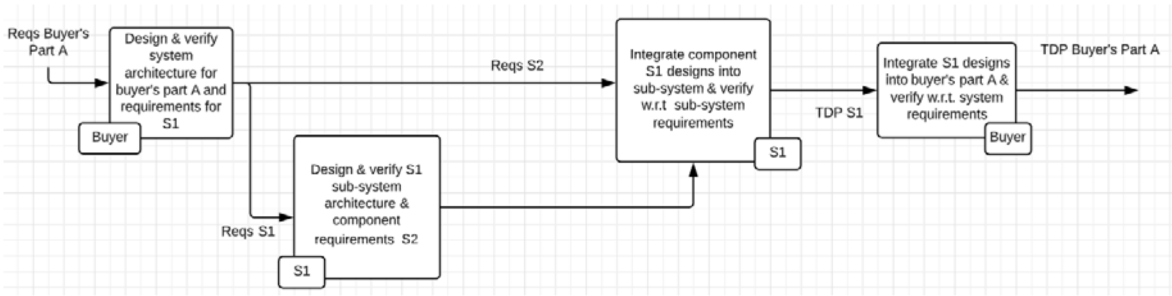

Figure 7: Vertical supply network design process flows with external design-make options for both S1 and S2.

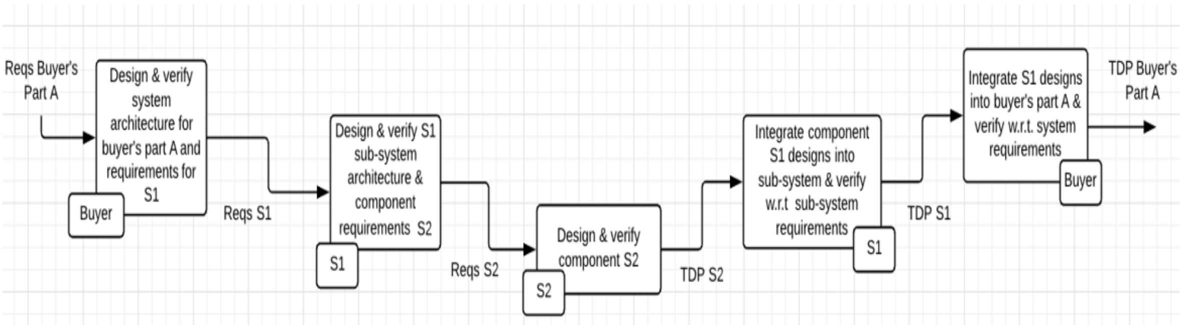

Figure 8: Vertical supply network design process flow with external design-make options for S1 and internal design and external make decisions for S2.

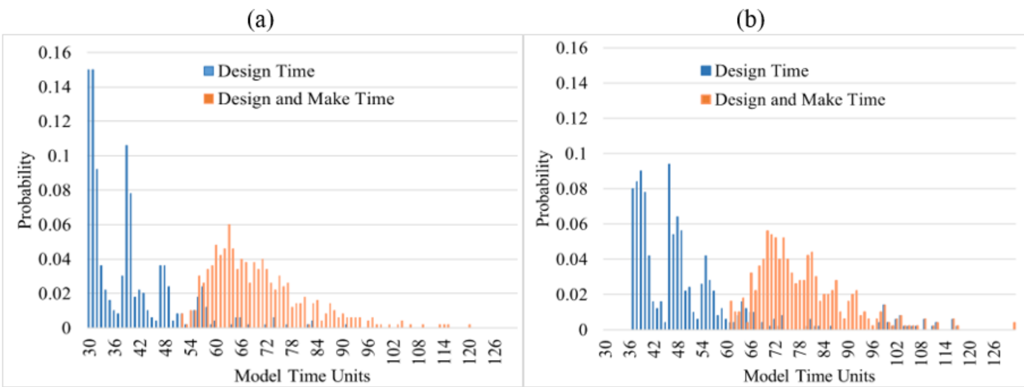

Figure 9: Times taken to run the model 500 times for (a) Scenario 1, (b) Scenario 2.

Undoubtedly, the models are not fully accurate as it was not possible in the study to validate all timings, variability, etc. The data are largely experiential, trusting on expert opinion. In addition, the simulation flows are somewhat approximate as in the real process the activities and phases in design can be more complex and specific to particular projects. But, the framework of the system vee and the superimposition of the process types in modular housing from literature have yielded promising results that have been validated (albeit as approximate) in our case study by the relevant company and industry personnel.

5 CONCLUSIONS AND DISCUSSION

This paper demonstrates an opportunity to use process simulation to quantify supply network risk early in the design process when design decisions can be used to change the structure of the supply network, and so to impact on the risk of the design. The majority of modular housing development activity is carried out off-site and the risks of time delays can have a huge influence on the expected lead time and overall project duration. The simulation design tool enables consideration of downstream implications of design decisions early in the design process, when crucial trade-offs of in-house or external sourcing decisions are made.

We acknowledge a number of challenges and opportunities for future studies. First, the scope of this study only included the design and make decisions during the off-site stage. Other construction processes such as transportation activities for completed modules and on-site assembly were outside the scope. Future studies could take a more holistic approach to involve both off-site and on-site stages of modular housing development. Second, data accessibility across the supply network involving multiple organizations is difficult, especially involving proprietary design and make information and complex inter-organizational relationships. This study was mainly from the modular housing system integrator's perspective. Future studies can explore the relational dynamics within the supply network, and analyze how the power within supply networks changes over time. There are also opportunities to explore alternative sources of data, dynamic analysis of live data, and the use of industry standards. Indeed, the availability and quality of such data improves when more data are collected throughout all job roles. The increased use of machine learning and artificial intelligence may have much to help feed such models. There are opportunities, too, to refine the processes and experiential data structures as models mature and their relevance and accuracy is assessed.

Third, this study adopted established supplier types of networks from literature and compared these to the bill of materials data shared by the case company. Four types of modular housing supply network configurations were identified and face-validated as representative of what potentially happens to modular housing system integrators and their attempt to manage supplier networks. We argue that the purpose of this current stage of study was to demonstrate the feasibility of the approach and, therefore, the data used to drive the simulation model, such as time requirements and probabilities of rework, are rough estimates. Future work is needed to collect data that can drive more realistic simulations. Lastly, modeling uncertainties related to delay and rework in the supply network (nodes and arcs) lies in identifying critical parameters. Future studies can look into potential root causes of delay and quantify critical attributes for the simulation.

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