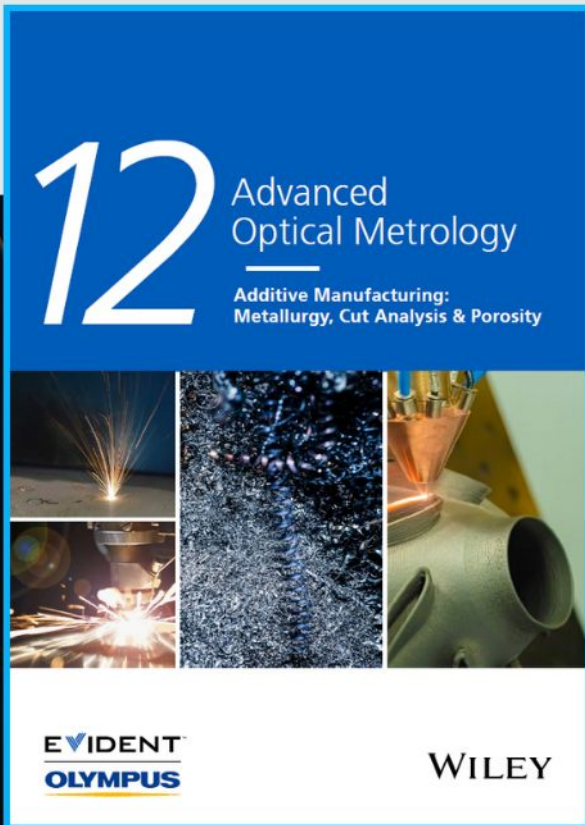




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The derivation and visualization of supply network risk profiles from product architectures

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Abstract

The architectures of extended enterprises, including the supply networks that design, develop and support large, complex, engineered products, often reflect system-level design decisions made very early in the product development process. Design tools used at this, preliminary design, stage focus on the physics and optimization of product system behaviors. Comparable tools for the consideration of extended enterprise perspectives at this stage are not available despite the costs of non-quality often attributed to supply chain issues related to early design decisions. This paper introduces an interface to a discrete event simulation package that derives supply chain processes from product system architectures, so enabling the quantification and visualization of supply chain risk in early design decisions. The interface uses input data, in the form of a product architecture and associated make-buy scenarios, which are available in the preliminary design process. Supplier data needed to drive the simulations is predefined and editable by users. Results from a proof-of-concept software prototype demonstrate the feasibility of generating enterprise architectures from product architectures and coupling these with a systems design vee model to create executable simulation models that can be used to identify, quantify and visualize engineering supply chain process operations and consequential risks.

KEYWORDS

extended enterprise, make-buy decisions, preliminary design, process simulation

1 | INTRODUCTION

Product architectures are specified very early in the product development cycle in response to design requirements that include customer (e.g., airline, airframe manufacturers and maintenance organizations), business and regulatory requirements. At these preliminary design stages, decisions are based largely on technical design requirements: primarily the physics and optimization of product and sub-system behaviors. However, these engineering decisions also have a significant impact on other critical design requirements such as those related to the need for effective and efficient supply chain operations. A num-

ber of authors report work on the impact of product architectures on supply chain performance from a business perspective. For example, Holweg and Helo¹ consider relationships between product and supply network configurations and Nepal et al.² consider factors in the design of product platform architectures on supply chain design and operation. In contrast, this paper takes an engineering design perspective and considers how knowledge on interplays between product and supply chain architectures might be used to inform decisions made in preliminary design processes for new products. Figure S1

The influence of early design decisions on supply network structures is particularly important in highly regulated sectors, such as aerospace,

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where details of production and other lifecycle processes, and the organizations that will deliver them, are a key part of the technical data package that contains the evidence on which certification decisions are based. Two key milestones in the certification of a new product are the decision (made by the prime contractor) that a given design is a candidate for certification and the decision (made by the regulator) to issue a type certificate for the design. This type certificate covers not only the design of the product but also downstream processes such as production, maintenance, repair and overhaul, all of which are critical to maintaining the airworthiness of a given product through its working life. The focus of this paper lies in the part of the product development process that sits between these two milestones: where test products, such as aero engines, are manufactured and the testing required for airworthiness certification is carried out. Both the manufacturing processes used and the organizations who carry out these processes are considered in the final certification decision, and any changes after a product has been certified require regulatory approval. At this stage in the product development process, schedule risk is a high priority because production of products for market cannot begin until the necessary certification has been gained.

The architectures of extended enterprises, including the supply networks that design, develop and support large, complex, engineered products, reflect [product] system-level design decisions made early in the product development process. For example, Huth et al.,³ highlight make-buy decisions, often made very early in the design and development process, as a key factor in overall project success. However, design tools used at this stage of product development focus on the physics and optimization of [product] system behaviors. Comparable tools for the consideration of supply chain perspectives are not available despite the costs of non-quality often attributed to supply chain issues. For example, the UK's Crossrail project lessons learnt include recommendations for the management of quality in supply chains.⁴ The purpose of this paper is to introduce a proof-of-concept software prototype that demonstrates the feasibility of generating a supply chain structure from a product structure and an associated make-buy scenario. The resulting supply chain structure is coupled with a systems design vee model⁵ to create an executable supply chain process simulation model. The model is imported into the simulation package to enable the identification, quantification and visualization of supply chain schedule risks in early design decisions. In addition to these technical requirements, there is an equally critical requirement to avoid increasing the resources (e.g., time and expertise) needed for preliminary design. To this end, the software prototype uses input data that is already available in preliminary design and generates output data that is suitable for use by designers with limited or no specialist knowledge of supply chain management or process simulation tools.

The approach introduced in this paper integrates research in three areas of work, extended enterprises, design and make supply chains, and make-buy decisions, into a product development context (see Section 2). In this way, we form key design requirements for the approach introduced in Section 4. These design requirements and the research methodology used to establish the approach are outlined in Section 3 and a case study used to evaluate the approach is provided in Section 5.

Finally, in Sections 6 and 7, we discuss the implications of this work for the development of future design tools and consider issues that would need to be addressed to realize such tools.

2 | BACKGROUND

Significant lifecycle costs are committed very early in the design process when there is limited knowledge of the design. For example, Asiedu and Gu⁶ report that over 70% of lifecycle costs are committed in this way. An early stage of a product's lifecycle is manufacturing, where the product begins its life, but these costs continue through the entire life of the product and are increasingly important for the complex networks of organizations who operate and support large, complex, engineered products through and at the end of their lives. Extended enterprise system architectures, including the supply networks that design, develop and support such products, often reflect system-level design decisions made early in the product development process.⁷ However, design tools used at this stage of the development process focus on the physics and optimization of [product] system behaviors. Comparable tools for the consideration of extended enterprise perspectives are not available despite the costs of non-quality often attributed to supply chain issues. Browning and Eppinger⁸ report early work on product and process architectures and highlight the need to trade off delivery time (related primarily to process architecture) and quality (related primarily to product architecture) to deliver maximum value to customers. Sosa et al.⁹ explore implications of mismatches between organizational and product architectures and how entrenched organizational relationships can have a detrimental impact on design innovation. Further, Gokpinar et al.¹⁰ introduce the term "coordination deficit" as a means to quantify mismatches between product architectures and organizational structures and conclude that this affects product performance. Their work uses engineering change orders as a measure of product development performance, and takes a system of systems view of the product, meaning that relationships between parts are functional and physical interactions between parts. In contrast, the research reported in this paper regards the product as a system of sub-systems and so the relationships in the product architecture are part-whole relationships.¹¹

DeRosa et al.¹² propose a research agenda for the engineering of complex systems that includes the question, "How can we better model, visualise and understand networks of interdependencies, to achieve insights on the likely consequences of variations and perturbations (e.g., impact of changes to schedule or changes in performance of one component on other parts of the enterprise)?" A number of authors have proposed responses that address this question. For example, Potts et al.¹³ explore the use of graph theoretic analyses to support the design of system architectures. Shaked and Reich¹⁴ propose a method for designing systems of systems that includes two core concepts: artefact and activity. In this vein, a number of authors report applications of Design Structure Matrix (DSM) to analyze product development processes. For example, Son et al.¹⁵ report an application of DSM to identify improvement opportunities in the

Boeing supply chain; and Batallas and Yassine¹⁶ report an application of DSM to support the social network analysis of the teams involved in the design of an aero-engine. A common theme in these applications are detailed descriptions of the architecture of the product, which for Son et al. and Batallas and Yassine form the axes of the DSM, and a process framework with which it is combined to support subsequent analyses. However, the product architecture is at a level of detail that suggests the analyses were carried out after the product architecture had been designed. This paper responds to DeRosa et al.'s question by exploring the feasibility of design tools that can be used as part of the design process, to enable evaluations of supply chain implications for alternative product architectures, before the design has been fixed. If successful, such tools could be used to integrate complexity science-based analyses into early product development processes.

Dong et al.¹⁷ identify as a source of complexity the influence of the product design on the design of the organization (including its structure and processes) that will deliver the product to market and support it through life. This creates particular challenges in preliminary design when the product design does not exist because it is under development and, as a result, the organization design is uncertain. The key contribution of this paper is a general purpose approach that can be used in preliminary design to explore the consequences of early design decisions (related to the design of the product architecture) on subsequent design and manufacturing organizations and processes. A number of authors (including Daub et al.¹⁸; Kannan et al.¹⁹; Lender et al.²⁰) introduce approaches for the design of system architectures. Daub et al., for example, provide an approach for the optimal design of process structures with respect to flexibility and cost which relies on product architecture and design requirements. In a similar vein, Kannan et al. introduce a value based systems engineering approach for design decomposition (to form system architectures) and couplings between sub-systems. They currently use design variables but future work includes operational environments. The approach introduced in this paper provides a mechanism for linking product architectures to process simulations that are key to the design and optimization of operational environments. In contrast to Lender et al., who introduce a DSM-based approach for the design of system architectures that links functional and physical product structures, we relate physical structures to supply chain process structures. A key benefit of both approaches lies in the possibilities they create for subsequent activities such as risk management. Lender et al. refer to these opportunities but focus on the design of the system architectures rather than their future use. In this paper we provide an early demonstration of the possible uses of such approaches by enabling the visualization of supply chain schedule risk profiles based on design decisions related to alternative product architectures.

A number of authors provide approaches for the management of engineering supply chain risk that begin with the identification of risks but all relate to post-certification production processes where delivering orders in full and on time, and minimizing costs, are priorities. To our knowledge, none relates to precertification processes where the priority is to gain regulatory approval for the design and its life-cycle processes (e.g., production, maintenance, repair and overhaul) as

quickly as possible. Oliveira et al.,²¹ in a review of simulation methods for supply chain risk management, identify disconnects between risk management, simulation and optimization methods as an important knowledge gap in supply chain performance measurement systems. The approach introduced in this paper could form a future tool for the identification of supply chain risk: the first stage of Oliveira et al.'s supply chain risk management framework.²¹ Fig. 9 The need for such approaches is highlighted in the tools and techniques listed by Oliveira et al., none of which reflect the product architecture which has such a significant impact on supply chain structure and so its operation and risk. Suffo and Brome²² provide a methodology for risk management in the aeronautical sector which, similar to Oliveira et al. and others, such as Benedito et al.,²³ include risk identification, assessment, action, implementation, and control and monitoring. By focusing on the identification of risk, both Suffo and Brome and this paper provide decision makers with opportunities to select design alternatives based on supply chain risk. There is also a large literature on risks related to supply chain costs. Given this paper's focus on schedule risk in precertification processes, supply chain cost modelling literature is out of scope but, as with other forms of supply chain risk, the role of supply chain structure cannot be ignored. For example, Agar et al.²⁴ provide a review of cost estimation strategies and associated uncertainties in the early concept design of small modular reactors which, from the examples provided in the paper, depends on the reactor's product architecture and downstream life cycle processes that are specific to this kind of product.

3 | RESEARCH METHODOLOGY

The approach introduced in this paper is the result of research spanning almost 20 years that has involved the development of software prototypes evaluated using case study data with target users. In recognition of the observation that engineering supply chain and other organizational structures tend to mirror product architectures,²⁵ an initial extended enterprise design tool was proposed by McKay and de Pennington.²⁶ This enabled the analysis of extended enterprise configurations with respect to Fine's electronic proximity measure. However, a key limitation was the static nature of these network models. To produce dynamic models, for example, to enable process simulations, we needed a process model that reflected the activities being carried out by the organizations in the network and, for this process, a means of measuring process performance.

From work on design and make networks in the aerospace sector,²⁷ a need was identified for a design tool that, as early as possible in the design process, could be used to quantify and visualize supply chain implications of early design decisions when product architectures are being fixed. In addition to this primary functionality, key requirements were that such a tool was (i) usable by design engineers with limited time and supply chain knowledge, and (ii) used only data that was available early in the design process. A process simulation tool, version 22.0a of Lanner's WITNESS discrete event simulation systemⁱ, was

ⁱ <https://www.lanner.com/en-us/technology/witness-simulation-software.html>

BoM product structure			Make-Buy scenario	
			Design	Make
A			In-house	In-house
	B		External	External
	C		External	External
		D	External	External
		E	External	External

(A)

BoM product structure			Make-Buy scenario	
			Design	Make
A			In-house	In-house
	B		External	External
		D	External	External
		E	External	External

(B)

BoM product structure			Make-Buy scenario	
			Design	Make
A			In-house	In-house
	B		External	External
	C		External	External
		D	In-house	External
		E	In-house	External

(C)

FIGURE 1 Example used to introduce the approach

selected to support the quantification and visualization process. However, given that design engineers were unlikely to be process simulation specialists, it was decided to produce a simulation framework model in WITNESS that would read in automatically a product architecture and associated make-buy scenario and generate the required model logic from pre-built modules. The model would not only be created but also run automatically and generate results without the need for the engineers to open the full WITNESS interface. Excel was selected as the implementation platform for a range of reasons, primarily: the majority of engineering designers already use Excel in their daily work; it is straight forward to define a product architecture as an indented list in Excel; and WITNESS can be controlled from other programming languages and packages including Excel. For the interface itself, a target process was identified as the design and make process for test engines in the aerospace sector, and the time taken to design and produce a batch of test engines for use in testing needed for certification was selected as the performance measure. In line with Gokpinar et al.,¹⁰ the flow of change requests was selected as the process variable that had the biggest impact on time taken, especially those issued after the design of candidate engines had been completed and production of the test engines had begun. In the remainder of this paper we introduce the logic behind the interface and results of early evaluations with target users.

4 | PROPOSED APPROACH

This section uses a schematic example to introduce the six key stages of the approach:

- (i) Define a product breakdown structure and make-buy scenario;
- (ii) Generate a supply chain structure from the break-down structure and make-buy scenario;
- (iii) Elaborate the supply chain structure into a supply chain process;
- (iv) Translate the supply chain process into a discrete event simulation model;
- (v) Quantify, visualize and experiment with alternative product architectures and make-buy scenarios, and so supply chain risk profiles; and
- (vi) Compare supply chain risk profiles with each other.

In Section 5, we demonstrate its applicability to a real-world case study.

4.1 | Define a product breakdown structure and make-buy scenario

The example used to introduce the approach is a part, A, that has two breakdown structures shown in Figure 1. One (in (a) and (c)) is an indented parts list where Part A has two parts (Parts B and C) where C is a sub-assembly of Parts D and E. The other, shown in (b), is a flat parts list where Part A is composed of three further parts: B, D and E. There are three make-buy scenarios shown in Figure 1, two for the indented parts list ((a) and (c), Scenarios A and C, respectively) and one for the flat one ((b), Scenario B). This is all the information needed to generate supply chain structures for these scenarios. These examples are used because they illustrate the impact of different product structures (the

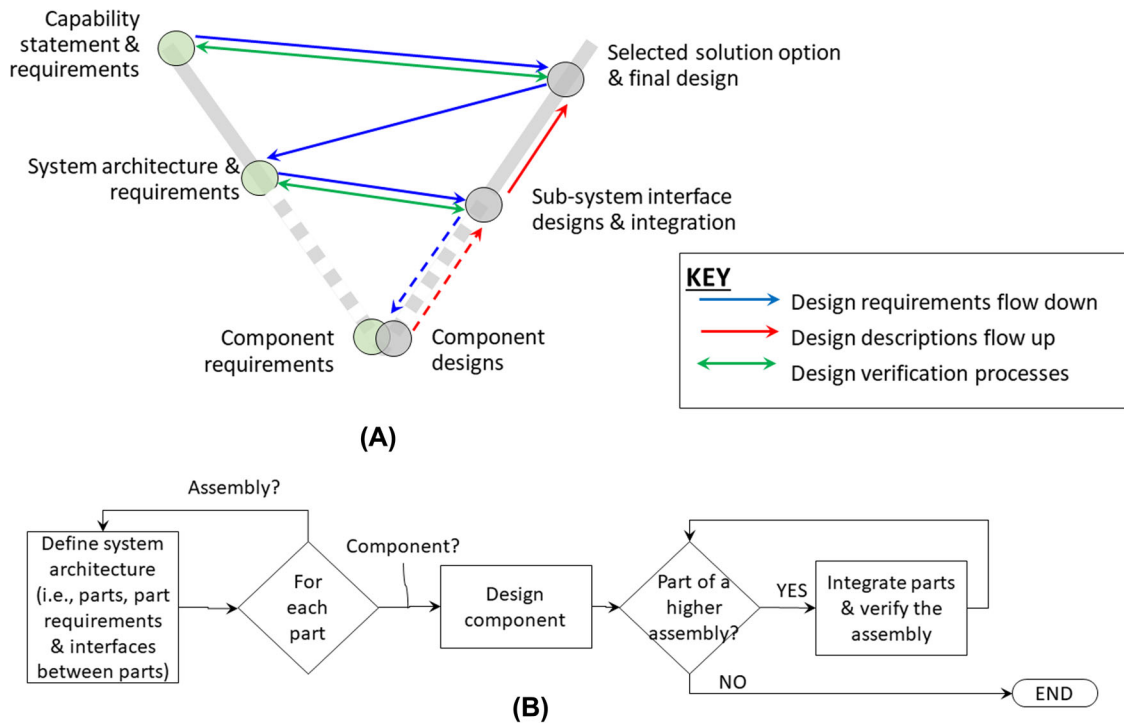


FIGURE 2 (A) The systems design vee model (adapted from: McKay et al., 2018⁵) and (B) the associated recursive system design process

one in (a) and (c) as opposed to the one in (b) and different make-buy scenarios for a given product structure (in (a) and (c)) on supply chain structure and associated risk profiles.

4.2 | Generate a supply chain structure

The approach builds on the systems design vee model shown in Figure 2(A).⁵ This model is a development of the left-hand side of the RAEng systems engineering vee model²⁸ and establishes an explicit relationship between a given product's architecture and its development process. The vee model acts as a recursive process template (illustrated in Figure 2(B)) that is elaborated through the development process depending on design decisions related to the product being developed and its architecture. In the process template, systems that are decomposed into further [sub-]systems are referred to as "assemblies" and are treated differently to systems that are not further decomposed which are referred to as "components". As a result, the design process structure varies depending on design decisions made during the development process; this means that it is not possible to define, a priori, a simulation model for a given system design process. The approach introduced in this paper addresses this issue by providing a mechanism that derives such a process from a given product architecture. We used the systems engineering vee but, in principle, there is no reason why the vee model could not be replaced with an alternative model, for example, to suit practises in specific sectors. Figure 3 shows the design processes that result for Scenarios A and C. In addition to the process structure, the key feature to note is the flows between

the process steps: requirements for each part (REQ), corresponding to the flow down of requirements on the left-hand side of the vee, and design descriptions, in the form of Technical Data Packages (TPD), corresponding to the flow up of design solutions on the right-hand side of the vee.

Given a product development process and a make-buy scenario, it is possible to establish which of the process steps are carried out by which organization. This is shown for Scenarios A and C in Figure 4 for the design aspects of the make-buy scenarios, and in Figure 5 the resulting design supply chain structure for Scenario A is shown. Key points to note are:

- (i) if a part is designed in-house then the organization responsible for the design of the parent part is also responsible for the design of the part (e.g., see Parts D and E in Figure 4(B)); and
- (ii) if a part is designed externally then a new organization is needed to take responsibility for the design of the part (e.g., see Parts D and E in Figure 4(A)).

The structure of the manufacturing portion of the supply chain (shown in Figure 6) is derived through a comparable process. However, instead of a systems design vee model with requirements flowing down and solutions (in the form of TDPs) flowing up, the vee model is for product realization where orders which refer to TDPs flow down the left-hand side of the vee and solutions, in the form of physical products, flow up the right-hand side of the vee. The whole design and make supply chain structure for Scenario C is shown in Figure 7 where it is superimposed on key phases in a double vee model for design and

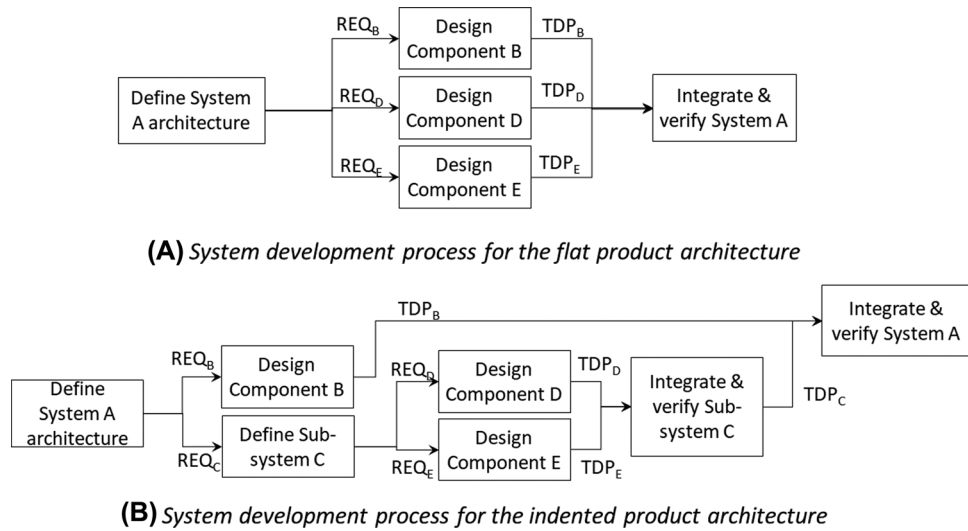


FIGURE 3 Systems design process elaborated for the two product architectures: (A) Scenario B and (B) Scenarios A and C

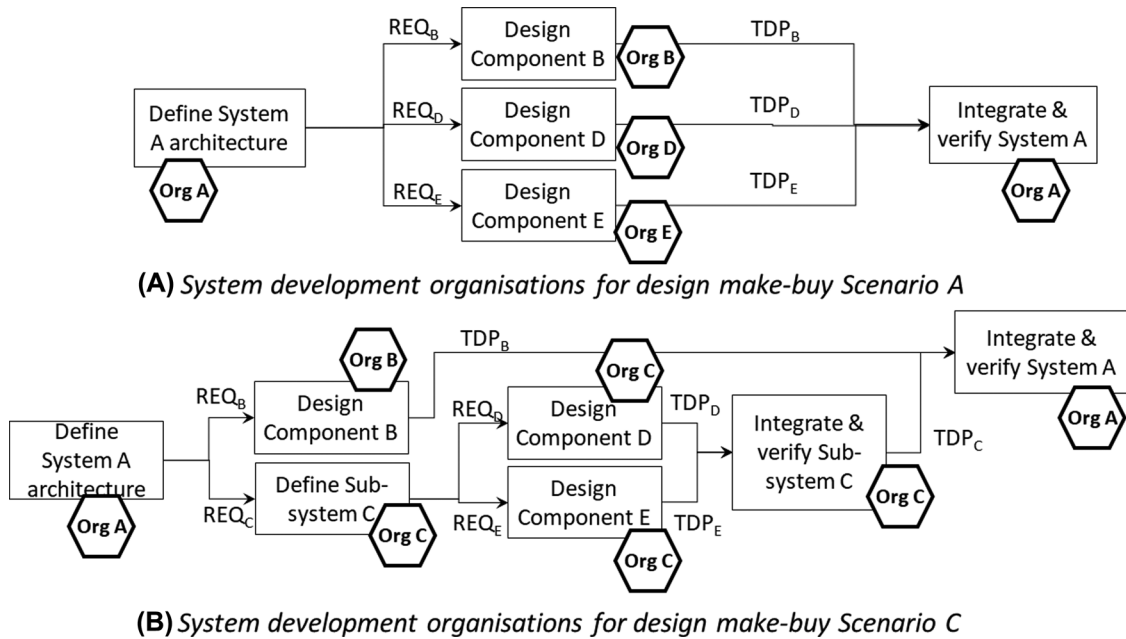


FIGURE 4 Systems design process annotated with the organizations that will complete each design activity

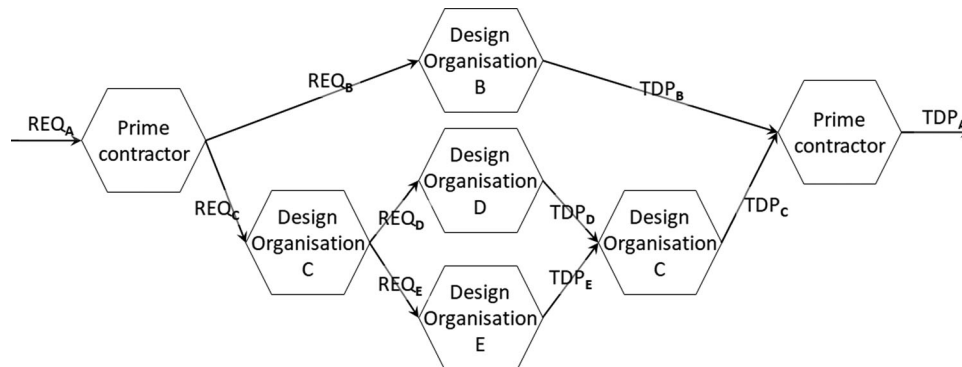


FIGURE 5 Design supply chain for the design part of Scenario A

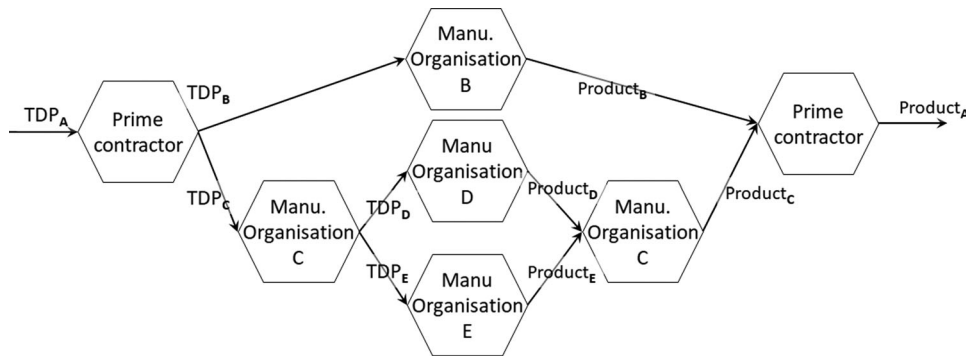


FIGURE 6 Manufacturing supply chain for the make part of Scenario A

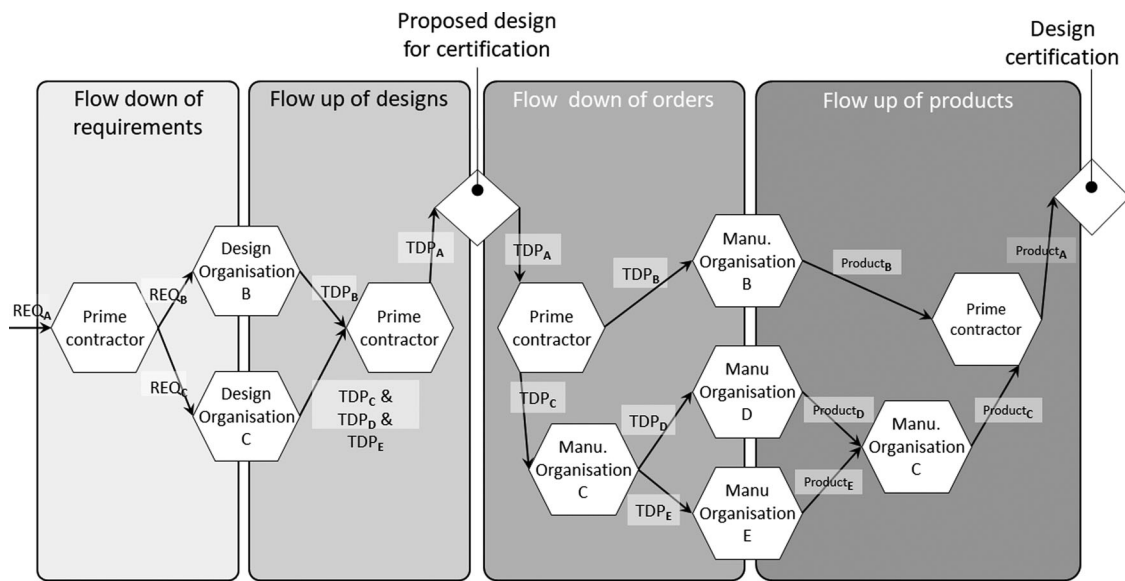


FIGURE 7 Design and make supply chain structure for Scenario C

make operations. This double vee model reflects the structure of the aerospace sector where two key milestones are the definition of a proposed design for certification at the end of the design phase, and a certified design after test products have been produced and tested. If the approach reported in this paper was applied to other sectors then this double vee model may need to be adapted accordingly. In addition, the flow-down of orders reflects purchasing practices in the civil aerospace sector. It was needed in the model to accommodate the regulatory requirement in the civil aerospace sector that the chief engineer in the prime contractor organization is responsible for the entire design. As a result, any requests for changes from manufacturing (as discussed in Section 4.3) need to be approved by the prime contractor organization; the flow down of orders provides the necessary connectivity between the design and make operations. We are aware of other purchasing practices and, again, if this approach was applied in a new context then this aspect of the model would need to be reviewed. In this research, given its focus on the design process and the small volumes of test engines produced, the number of products ordered was not considered.

4.3 | Elaborate into a supply chain process

The process that each organization carries out at a given point in the supply network depends upon its location in the double vee model and the part that it is working on. Details of the processes at each stage of the double vee are shown in Table 1. It can be seen that the process steps reflect the activities in the systems design vee model and whether the item being processed is a component or an assembly. The results of applying this to the Scenario C supply chain structure are shown in Figure 8 where, for clarity, the organizations are shown in white text on black hexagons associated with each process step.

To form the basis of an executable simulation model, a process such as the one shown in Figure 8 needs more detailed characterizations of its process steps. Given the focus on schedule risk, for this research these attributes related to the time taken for each process step. However, if the approach was used to assess a different performance indicator then these attributes would need to be adjusted to reflect this. The timing data used in the current version of the interface is shown in Table 2. There were a number of challenges in establishing

TABLE 1 Supply chain processes

Location of organization in the double vee	Flow in	Process	Flow out
Flow down of requirements	Requirements for target product/system (which may be a sub-system)	Design	Specify target product architecture and requirements for its sub-systems
Flow up of designs	Requirements for target product		For assemblies, design target product and specify sub-system requirements For components, design and verify target product
There is no overlap between flow up of designs and flow down of orders because design must be approved as a candidate for certification before orders are placed			
Flow down of orders	Volume of target product required	Order	Place order for target product
Flow up of products	Volume of target products required	Make	For components, manufacture and verify target product
For assemblies, integrate parts and verify assembly			
			Integrate and verify input products to form target product
			Required volume of target products

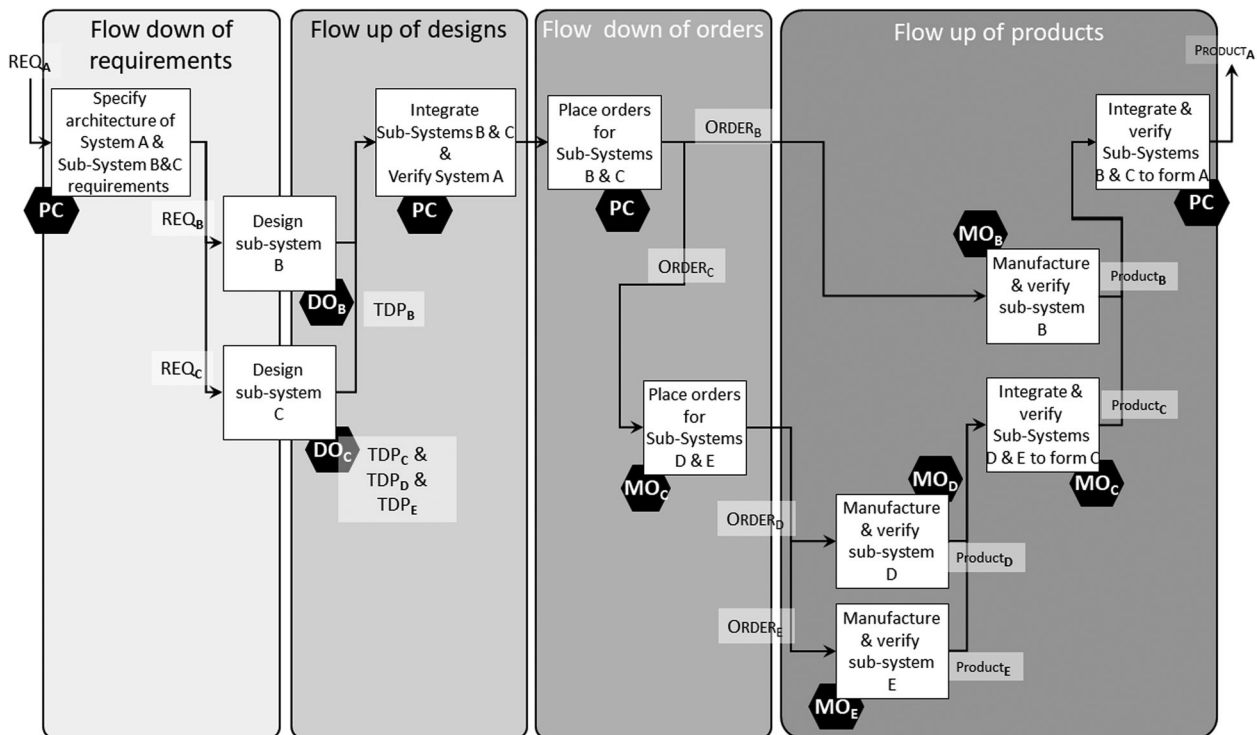


FIGURE 8 Supply chain process flowchart for Scenario C (Key to organizations: PC - Prime Contractor; DO_N - design Organization N; MO_N - Manufacturing Organization N)

TABLE 2 Estimates of times taken for each kind of process step

Activity	Relative time units
Manufacture a component	1
Design a component	5 (i.e., 5 × manufacture)
Manufacture a system (or assembly) with n parts	$0.1 \times n(n-1)$
Design a system (or assembly) with n parts	$0.5 \times n(n-1)$
Integrate designs to form a system (or assembly) with n parts	$0.5 \times n(n-1)$
Place an order	0

values for these attributes. The root causes of these challenges were: (a) the time taken to design a given product (i.e., designing either a fully defined component suitable for use by a manufacturer or a sub-system architecture and requirements for each sub-system suitable for a design supplier) is not typically known and (b) the time taken varies depending on the complexity of the design. However, given that our goal was to generate risk profiles that could be compared with each other rather than absolute times taken, we used relative timing data based on two rules of thumb. Firstly, the time needed to manufacture a component is *one* time unit provided the design is complete and correct and the time needed to create such a design is *five* times longer than the time to manufacture it, and so takes *five* time units. Secondly, for assemblies, all possible interfaces between parts, whether required or not, need to be considered so the relative time needed to process an assembly is related to the number of possible interfaces between parts, that is, $n(n-1)$, where n is the number of parts. The same relative times for components were used for assemblies (i.e., design (x5) and manufacture (x1)) and, again a rule of thumb, the time needed for each interface was one tenth of the time needed for a component. The results of this are shown in Table 2. As already noted, these are estimates and, if the interface was used in real-world settings, they would need to be validated and adjusted accordingly. In the implementation of the interface, the component design and manufacture times for each part are captured in a spreadsheet so these are straight forward to modify after the supply chain structure has been generated and before the simulation model is run. For simplicity, the times related to the design and manufacture of interfaces between parts are implemented in Visual Basic so only editable by further coding. The time for placing orders was deemed to be negligible and so assigned a time of zero; the placing of orders was included in the model to provide traceability for rework (see previous paragraph) and its inclusion reflects airworthiness regulatory requirements related to the responsibilities of the chief engineer in prime contractor organizations.

Combining this data with the supply chain process in Figure 8 creates a deterministic model that will always take the same amount of time to run, that is, the time of the slowest path through the process. In practice, supply chain risk arises from randomness within the process. The sources of this randomness vary according to the process under consideration and the purpose, and so priorities, of the simulation. This research focused on the design and development of aero engines

from initial design requirements through to a certified design. The certified design includes both an approved definition of the engine and an approved manufacturing process. As shown in Figure 7, there are two key milestones in this process: the definition of a proposed design for certification and the certified design itself. From discussions with industry specialists, and although there is randomness in the design process itself, the main source of schedule risk lies in the manufacture of the test engines, that is, in the second of the two vees in the double vee model, which leads to a need for rework in both design and manufacture. Randomness in individual process steps can be captured using standard simulation package tools to define probability distributions for the time taken by each of the steps. However, in the current implementation, variation in the time of each process step is not captured because it was considered to have a limited impact on the time taken when compared with the impact of rework loops. In addition, the purpose of the research was to demonstrate the feasibility of using supply chain simulations in preliminary design processes to inform design decisions related to product architectures and associated make-buy scenarios. Before it is suitable for use in industry, further work is needed to build understanding of what would be the most appropriate forms of distributions and sensitivity analyses to identify the most important supply chain parameters. In general, all models are of course just that, models, and we are aware that data in this area is largely in the heads of experts (to date). However, the necessary accuracy of a given model depends on its purpose and more work is needed to assess the feasibility of accessing more accurate data at an early stage (e.g., by using databases of experience coupled with expert amendments for specific industry sectors).

Rework, on the other hand, cannot be modelled using data within individual process steps because it spans multiple steps. In practice rework can be triggered through the entire design and make process. However, the approach reported here focused on rework triggered by requests for concessions after a design has been approved as a candidate for certification but before it has been approved for certification (i.e., in the *Flow up of products* regions in Figure 7). The rationale for this was that the majority of significant schedule delays in the development of aero engines were attributed by industry experts to concessions raised during manufacture, after a candidate design for certification had been approved, rather than across the different stages of the design process. For this research, rework has two key characteristics: a need for rework, which appears randomly in the manufacturing process through requests for concessions, and the degree of rework, which governs how far back in the design process a given rework task must return. Together these characteristics result in randomly used feedback loops across tiers in the supply network. Again, the models could be enhanced to include more detail on this in future. However, the granularity of the model that can be created is somewhat dependent on the data available (either from collected data or expert opinion) and affects both the accuracy and usefulness of the model. For this reason, and as with any model, for any chosen level of simplification a model needs to go through a validation process before use in real-world applications. Table 3 gives the parameters used to characterize rework in this study. The values were used to generate the results presented in this paper

TABLE 3 Probabilities for whether rework will be raised and, if so, its extent (i.e., the number of stages back in the process that need to be redone)

No stages back	Requirements need rework (applies to components)(applies to assemblies)			TDP needs rework (applies to assemblies)			Concessions	
	1	2	3	1	2	3	Request Raised	Rejected
Assembly - Internal	-	-	-	0.15	0.1	0.05	0.2	0.1
Assembly - External	-	-	-	0.3	0.1	0.05	0.1	0.1
Component - Internal	0.1	0	0	-	-	-	0.2	0.1
Component - External	0.1	0.05	0	-	-	-	0.1	0.1

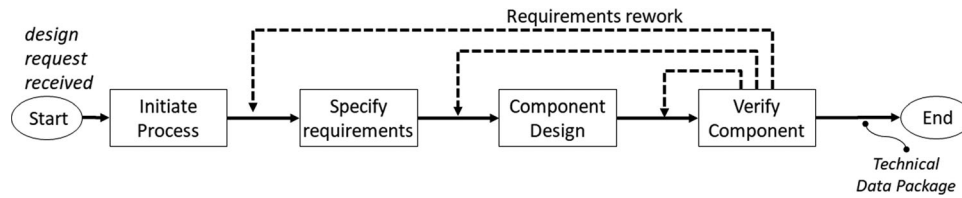


FIGURE 9 Schematic of the pre-built component design process simulation module

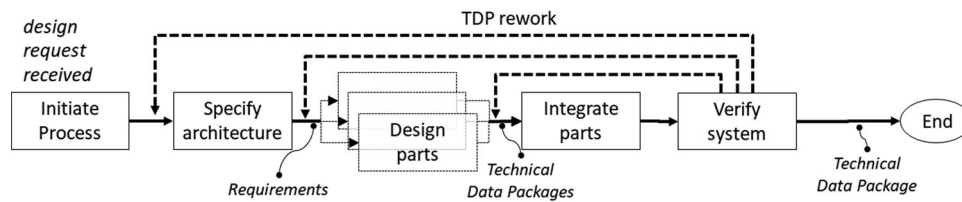


FIGURE 10 Schematic of the pre-built assembly/system design process simulation module. NOTES: (i) Specify architecture includes specification of sub-system requirements;(ii) The Design components step is expanded using the template in Figure 9

and the same limitations apply as those in the discussion of Table 2. Like the process time data in Table 2, in our implementation the values in Table 3 are stored in a spreadsheet so can be easily adjusted.

The data related to the degree of rework, again in the form of probabilities, are on the left-hand side of Table 3. As can be seen from the column headings, two factors are used to specify the degree of any given rework process. These are (1) the number of design process steps across which a given request creates rework, and (2) whether this rework is of the design requirements (which applies to components) or the design definition (i.e., the TDP, which applies to assemblies). To explain how these work, more detail is needed of the design process models used in the pre-built design process simulation modules (see Figures 9 and 10). In the current implementation, components are only subject to rework on requirements and these come from the design process for the assembly that is the component’s parent in the BoM. Given this, the result of any rework is verified against the requirements and, once a component design has been verified, a TDP is output. For assemblies, on the other hand, requirements are received from the design process for the assembly’s parent in the BoM. These are passed on to the design processes for the assembly’s immediate children (“Design parts” because the assembly’s children may be

components or assemblies) in the BoM. The assembly design process then receives TDPs for the assembly’s parts from the tiers below which it integrates to form the reworked assembly design and associated TDP.

Figure 11 shows how these two modules are used as templates to generate a process model for the simulation of the design of system A and sub-system B from Figure 8. If a change request is raised, for example, in the manufacture of Component B, the request is cascaded back through the design and make chain to the design organization for Component B. In this example, Component B is outsourced by the Prime Contractor (PC) to Design Organization B (DO_B) meaning that the design process in DO_B is initiated. Within this process, there are rework loops that may be invoked. Whether a given rework loop goes back one, two or three tiers is governed by the probabilities given on the left-hand side of Table 3. As can be seen from Figure 11, the outsourcing of the design means that, at times, the rework loops span multiple organizations. For example, if the rework loop taking three steps back in the design of Component B is triggered then this creates rework for PC and then DO_B.

The design process for each part is triggered when the design process is initiated and during manufacture when requests for concessions

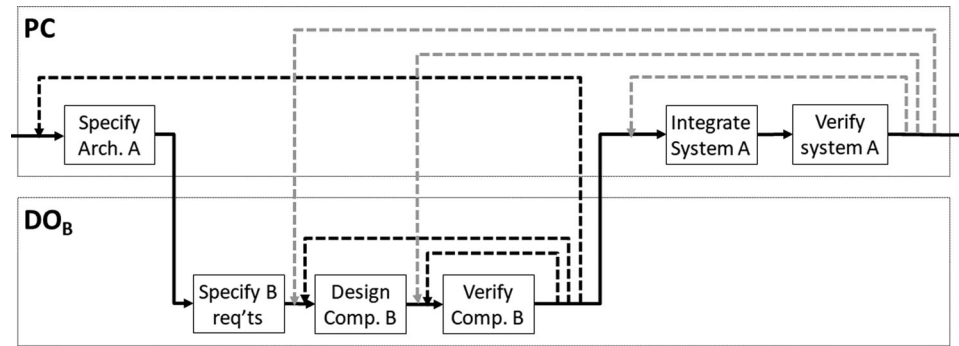


FIGURE 11 Schematic of the simulation model for the design and verification of System A and Component B derived from the simulation modules in Figures 9 and 10

are raised. The data related to the need for rework, in the form of concessions, is in the two right-hand columns of Table 3. These are the probabilities that a concession request is raised and, once raised, whether it is rejected or not. For example, the data on the first row says that there is a 20% chance of a concession request being raised for an assembly that was designed in-house, and, as with all requests, there is a 10% chance that the request will be rejected. For the 90% of requests that are not rejected, rework activity is triggered in the design process starting at the prime contractor in the flow up of designs stage of the development process (e.g., PC, “Integrate sub-systems B&C & Verify System A” in Figure 8).

Together, the rework loops within the design process and the rework resulting from requests for concessions create the schedule risk reflected in the risk profiles generated. Given a need for rework to be carried out by an organization, the third factor that affects the speed with which rework can be completed, and so schedule risk, is each organization’s design capability. For this research, organizational capability is the combination of competency and capacity. In the aerospace sector, all candidate suppliers have completed a supplier selection process that confirms their competency. For this reason, organizational competency was not treated as a schedule risk factor but the capacity of each organization in the network was. In this paper, capacity is a measure of the resources available within an organization to deliver one or more processes. We quantify capacity as the number of simultaneous processes an organization can carry out, using a value of *one* for low capacity and a value of *five* for high capacity. Like the process times in Table 2, this is held in the Excel spreadsheet so straight forward to change before the simulation model is created.

4.4 | Translate into a simulation model

As is evident from the process model in Figure 8, which corresponds to an unusually simple product architecture, the time needed to create a simulation model, even for an expert user, would be significant. For use in design this is prohibitive because, in addition to the development of simulation models requiring skills not typical in a design engineer, the time needed to create multiple models for alternative product architectures and make-buy scenarios is unlikely to be available. For this

TABLE 4 Number of concessions raised in 1000 runs

No of concessions	Count	No of concessions	Count
0	533	4	9
1	310	5	2
2	117	6	1
3	28		

reason, in this research we streamlined the process of model building using pre-built modules and the automatic creation of models through code. In this way the simulation model is built in seconds and can be run quickly for efficient evaluation of scenarios early in a design process when designers are making trade-offs in the design of product architectures. Simulation models can also be used later in the product lifecycle, for example to test the design or operation of a manufacturing facility and its supply chain. There are many levels of digital twin that can be created to inform many different strategic, tactical and operation questions. The model framework created here could be extended for some of these, or indeed new models created using the simulation package interface.

4.5 | Quantify, visualize and experiment with supply chain risk profiles in the simulation package

Once created the simulation model can be run multiple times to create a risk profile for a given scenario. The histograms shown in Figure 12 are based on 1000 runs. Figure 12(A) shows the risk profile for Scenario C with a capacity of one for all organizations, and (b) the risk profile for Scenario C with a capacity of five for all organizations. Results of an initial analysis of the data used to produce the results given in Figure 12 are shown in Figure 13. From Figure 12, it can be seen that capacity impacts design and make time, and so supply chain risk. Further, from Figure 13, in general, simulation runs with fewer concessions take less time although this is not always the case. However, it should be noted that there were few instances of runs with five or six concessions (see Table 4) which would explain why those are misaligned.

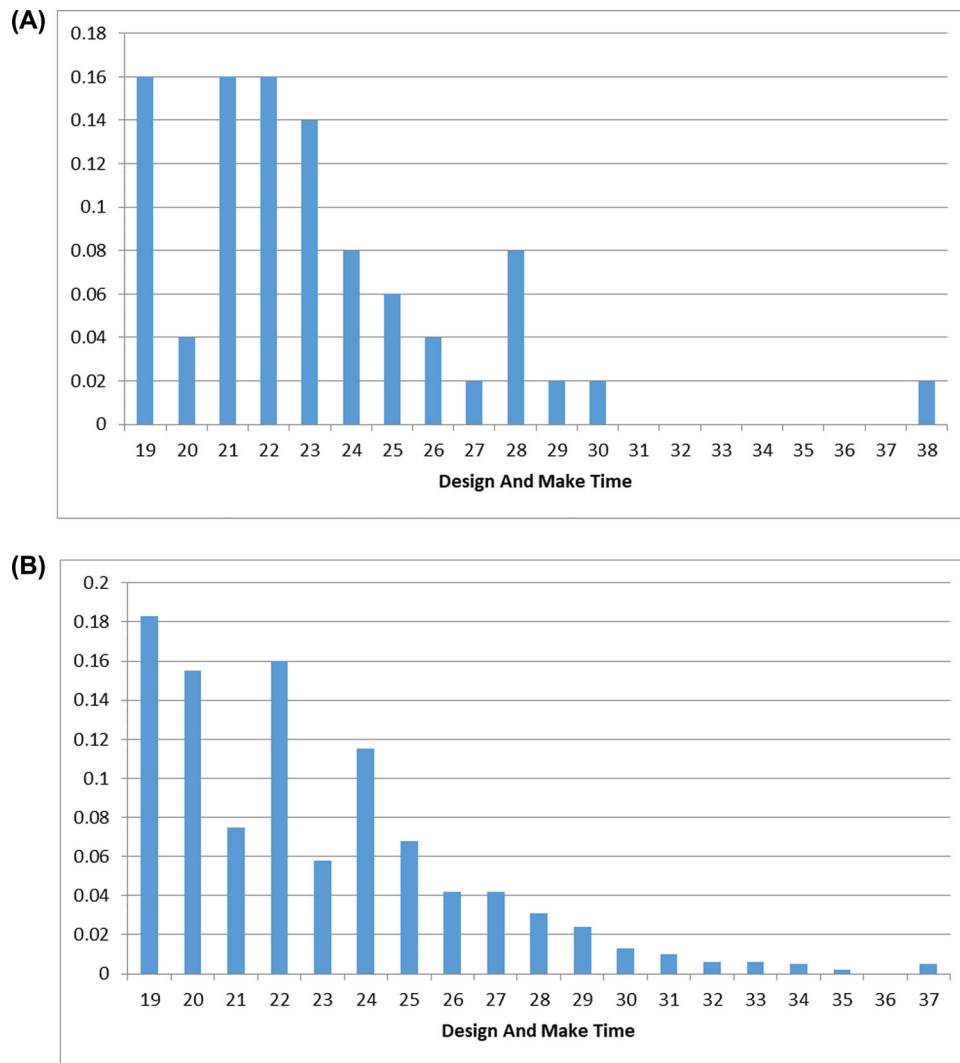


FIGURE 12 Risk profiles for Scenario C with low (A) and high (B) organizational capacities (NOTE: In both charts, the X-axis is the time taken (in simulation system time units) for the supply chain process to run and the Y-axis is the probability that the supply chain process will take each amount of time.)

4.6 | Visualize and cross-compare supply chain risk profiles in Excel

Each of the histograms in Figure 12 provides a quantification and visualization of risk for a single make-buy scenario. However, they are difficult to compare with each other because the x-axes have different scales, related to the range of times taken in the given simulation. To enable comparison of alternative profiles, the results of different simulation scenarios are exported to Excel where results for multiple make-buy scenarios can be visualized. The results of this for the example used in this section are shown in Figure 14 where the x-axis is the ranges of times taken and the y-axis is the probability that the time will fall into a given range based on 1000 runs of the simulation model. For the example used in this section, this results in a simple visualization but, as will be seen in the next section, such profiles provide more value in real-world cases.

5 | CASE STUDY APPLICATION

In this section we introduce a product case study that was used to evaluate the approach using available design data. The selected product, illustrated in Figure 15, was a ground support trolley that is used in the lifecycle support processes of an aero engine. The design data provided were the engineering drawings that define the product; these were used to create a CAD model from which the illustration and parts list in Figure 15 were derived.

Two product architectures (see Figure 16), each with four make-buy scenarios (see Table 5), were developed from the parts list which, in the assembly drawings, was the flat structure shown in Figure 16(B).

Design and make supply chain structures were generated for each of the make-buy scenarios. This resulted in four supply chain structures, corresponding to whether the product structure was flat or indented,

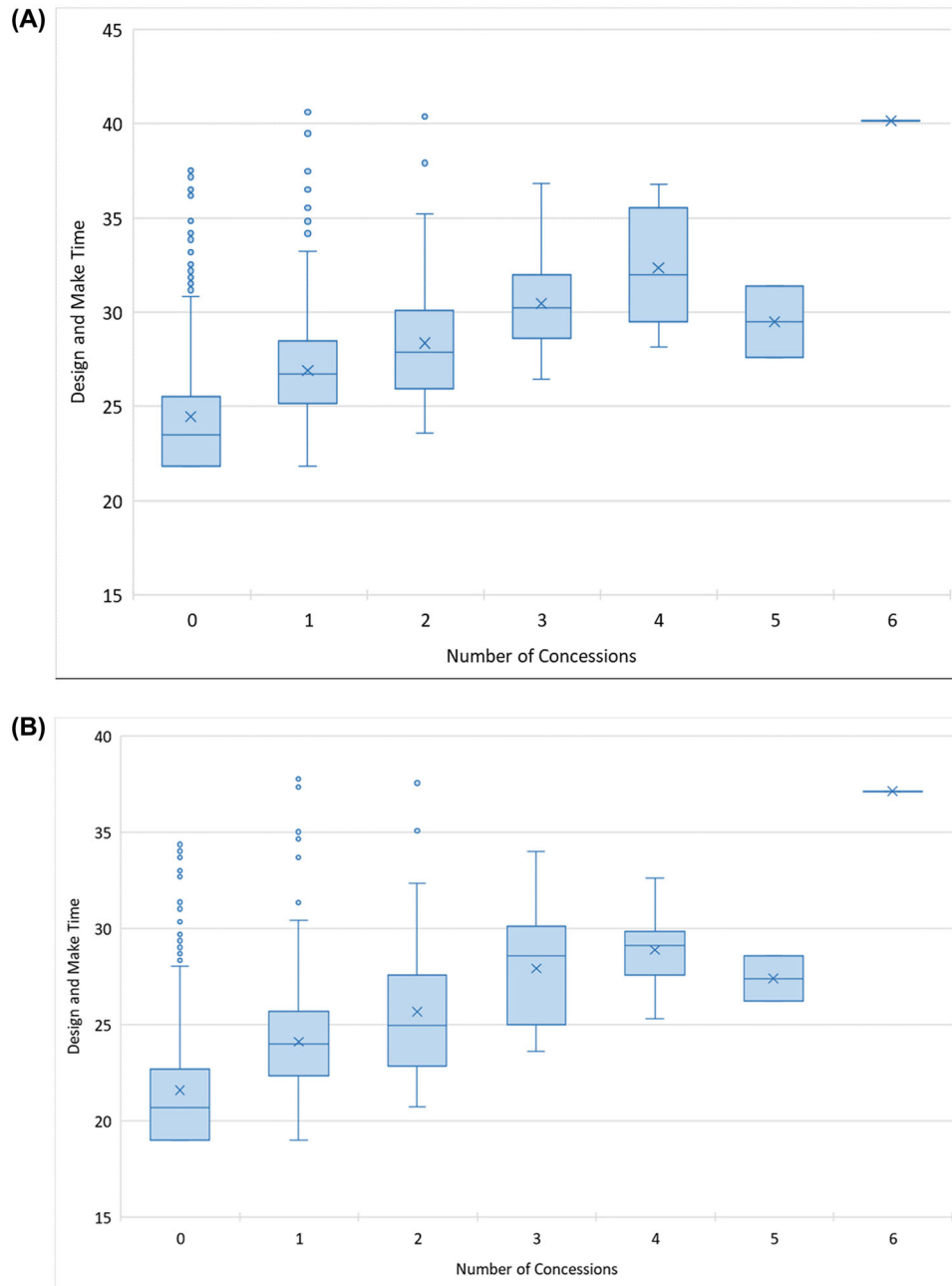


FIGURE 13 Whisker plots showing impact of number of concessions raised on design and make time for Scenario C with low (A) and high (B) organizational capacities

TABLE 5 Case study make-buy scenarios

Structure	Tier 1 make-buy	Capacity of prime
Indented	In-house	Low
		High
	External	Low
		High
Flat	In-house	Low
		High
	External	Low
		High

and whether the design and make processes for the Tier 1 parts, that is, those in the second column for each structure in Figure 16, were carried out externally or in-house. The supply chain structures for the indented and flat structures with the Tier 1 parts designed and made externally are shown in Figure 17. Two further supply chain structures were generated for the scenarios where the Tier 1 parts were designed and made in-house. Each of the four supply chain structures was simulated with two capacity levels for the Tier 1 suppliers: high (where the supplier can carry out five simultaneous processes) and low (where the supplier can carry out only one process at a time). A key point to note is that, in the current implementation, we do not take account of the number of a given part in an assembly. For design and make net-



FIGURE 14 Cross comparison of the two make-buy scenarios (Model 010 is Scenario C with low capacity for all organizations and Model 011 is Scenario C with high capacity for all organizations) (NOTE: the X-axis is the ranges of times taken for the supply chain process to run and the Y-axis is the probability that the run time for the supply chain process will fall into a given range.)

works, where a given part is designed once and manufacturing volumes are low, for example, because they are to build test products for use in the testing needed for certification, numbers of parts were not seen as a critical factor. However, this would need to be reconsidered if the approach was applied in other contexts. A simulation model was generated for each make-buy scenario and each was run 1000 times to evaluate the variation in results. The model is a discrete event simulation model and a particular application of Monte Carlo simulation because it includes stochasticity. Monte Carlo simulation also applies to other types of stochastic model, for example, where there may be no process/time component.

These resulted in the supply chain risk profiles shown in Figure 18. For this paper, the risk profiles for each scenario are grouped in a grid (see Figure 18(C)) where the axes are (in the columns) flat and indented product structures for both high and low capacity in the prime contractor and (in the rows) whether the Tier 1 parts in the product structure are made in-house or externally by supply chain partners. Enlarged views of the two charts in the top left-hand corner of Figure 18(C) are provided in Figures 18(A) and 18(B). Although it is possible to see overall trends from Figure 18, specifically that flat product structures tend to have a longer tail of longer times taken to design and make a test product, there are two limitations. Firstly, as the number of scenarios and the variations between them grows, the use of a tabular presentation becomes less feasible and secondly, as highlighted in Section 4.5, the x-axes on these profiles depend on individual simulation models and had to be manually adjusted for the figure. It is only possible to do this once all simulations have been completed and so the ranges of the x-axes known. Given this, to cross compare results, the chart in Figure 19 was produced. This is not limited to a specific number of models, the x-axis can be adjusted on the fly as changes become necessary and it provides a better visualization for comparison of risk profiles. When assessing results in Figure 19, it can be argued that the “best” scenario is the in-house manufacture of the design with the indented product structure and high capacity in the prime contractor. However, the available capacity is likely to depend on wider factors, such as the other projects that are being worked on at the same time, so other scenarios may be preferred. In addition, the risk profiles and associated simulation models can be used to identify and so facilitate the management of anticipated risks rather than avoid them.

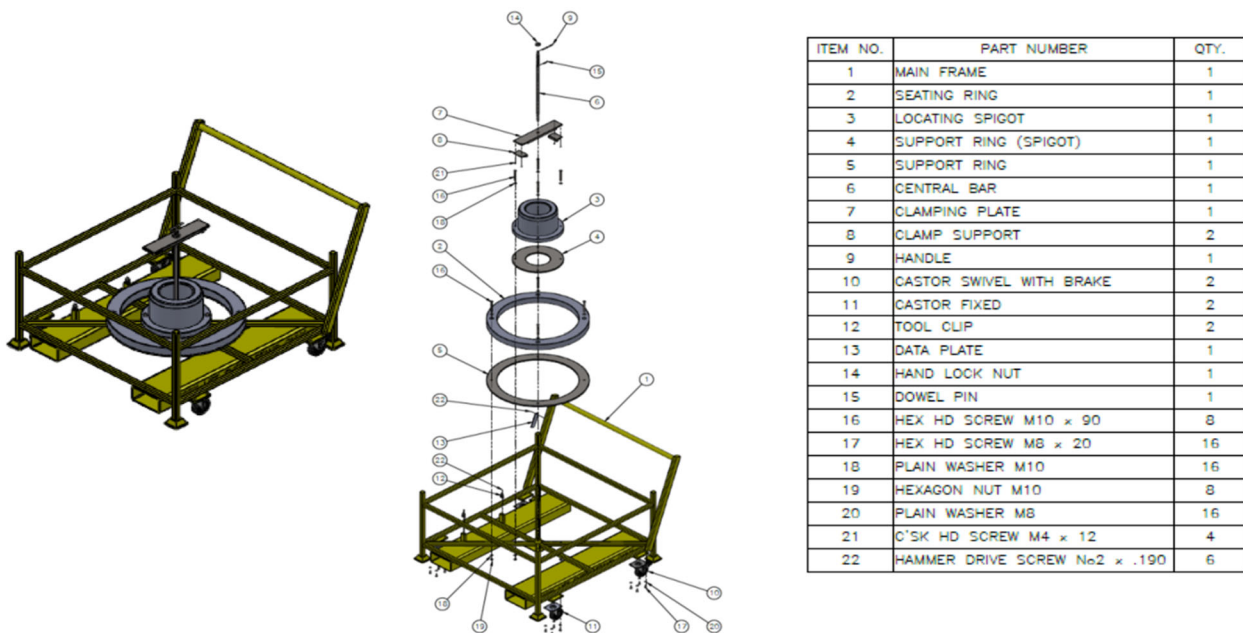


FIGURE 15 Ground support trolley case study

Parking trolley (1)		Parking trolley (1)	
	Main frame (1)		steelwork (1)
			data plate (1)
	Spigot assembly (1)		Support ring (1)
			Support ring (spigot) (1)
			Support ring (1)
			Support ring (spigot) (1)
	Pallet foot (4)		Support ring (1)
	Shaft assembly (1)		Central bar (1)
			Clamping plate (1)
			Clamp support (2)
			Handle (1)
	Wheel assembly (1)		Clamping plate (1)
			Clamp support (2)
			Handle (1)
			Fixed castor (2)
			Swivel castor (2)
			Tool clip (2)

(A) Indented structure

(B) Flat structure

FIGURE 16 Case study product architectures (NOTE: The numbers in brackets represent the number of parts in a single parking trolley): (A) Indented structure; (B) Flat structure

6 | DISCUSSION

This paper has introduced an interface to a discrete event simulation package that derives supply chain processes from product architectures, so enabling the quantification and visualization of schedule risks in engineering supply chains used to produce test products as part of design certification processes. An important feature of the interface is its use of input data (a system architecture and associated make-buy scenario) which are available early in the design process. In this way, we have demonstrated the feasibility of bringing supply chain thinking into early design processes without the need for engineering designers to become supply chain or simulation specialists, or spend time creating data sets for supply chain applications. However, further work is needed for such tools to become an integral part of day-to-day design processes. In this section we discuss three key areas: model validation, embedded domain specific assumptions such as those related to specific industry sectors, and the need for supplier and supply chain data.

The interface generates discrete event simulation models that are well-suited to supply chain processes where key events are the delivery of information and goods from one organization to another. The models and resulting risk profiles have been face validated with industry specialists but further work is needed to validate the simulation models, and so risk profiles that are produced, more objectively. This is challenging because, at the design stage, the networks being simulated do not exist in the real world. In addition, the necessary degree of accuracy is unclear and may well vary across application domains. However, in validating the models, it will be important to remember

that the risk profiles are relative to each other and intended for use in design trade-off decisions. If more accurate predictions of the time needed to design and make a given product configuration were needed then it would be better to calculate them using purpose-built simulation models. However, building such models would only be feasible later in the product development cycle when, for example, suppliers have been selected and so supplier data is available. By this stage of the product development process, many supply chain costs will have been designed into the product indicating a need for different kinds of supply chain simulation model with different degrees of validation and verification at different stages in the product development process.

The overall approach introduced in this paper is applicable to any situation where design decisions related to product architecture impact on supply chain structure. However, the interface itself has embedded within it several assumptions related to the industry sector (civil aerospace) for which it was developed. Some of these, such as the pre-built modules that represent processes within individual organizations and the process timing data, are straightforward to adjust because data values can be modified and alternative pre-built modules used. However, other assumptions are less straightforward to adjust because they permeate the entire interface. For example, the process structures used (such as the systems design vee model in Figure 2, the development process phases in Table 1, the double vee model introduced in Section 4.2, and the processes for the management of change requests reflected in Table 3) are based on practitioner experience and regulatory requirements in the civil aerospace sector. Adjustments would be needed for the approach to be applied in other sectors. For example, different industry sectors are governed by different regulatory

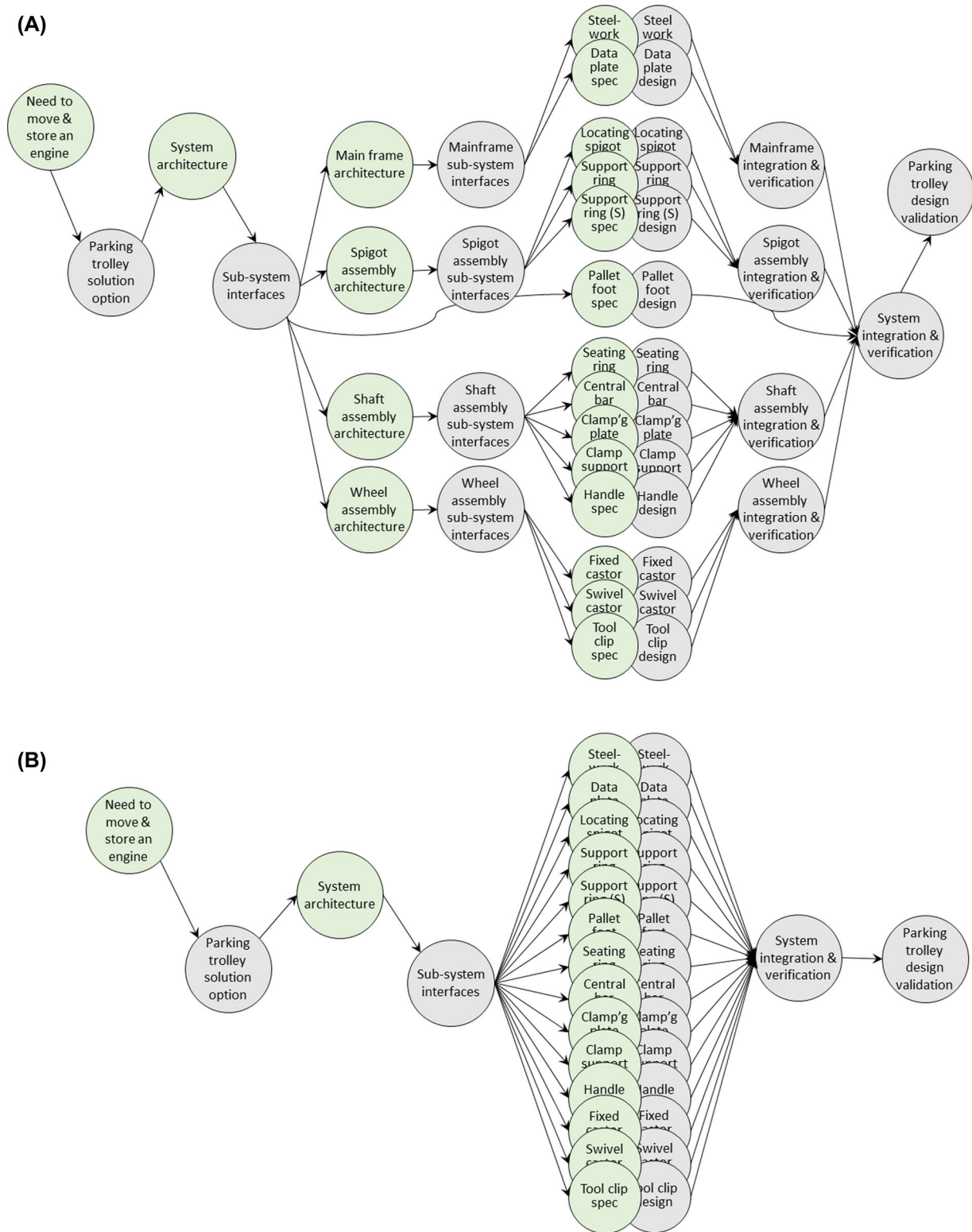


FIGURE 17 supply chain structures for (A) indented and (B) flat parking trolley structures

environments and the procurement strategies used vary across supply chains and the kinds of product being produced. Similarly, the process pathways used assume that each organization on a given tier purchases outsourced parts from its immediate sub-tier but we are aware of business situations where this is not the case. As a result, to be applied

in different business domains, the structure of the simulation models would need to be reviewed and adjusted accordingly. Further, the make-buy scenarios shown in Figure 1 assume that only design and make operations can be outsourced and only two options, in-house or external are provided. In practice, supply chains are more complex and

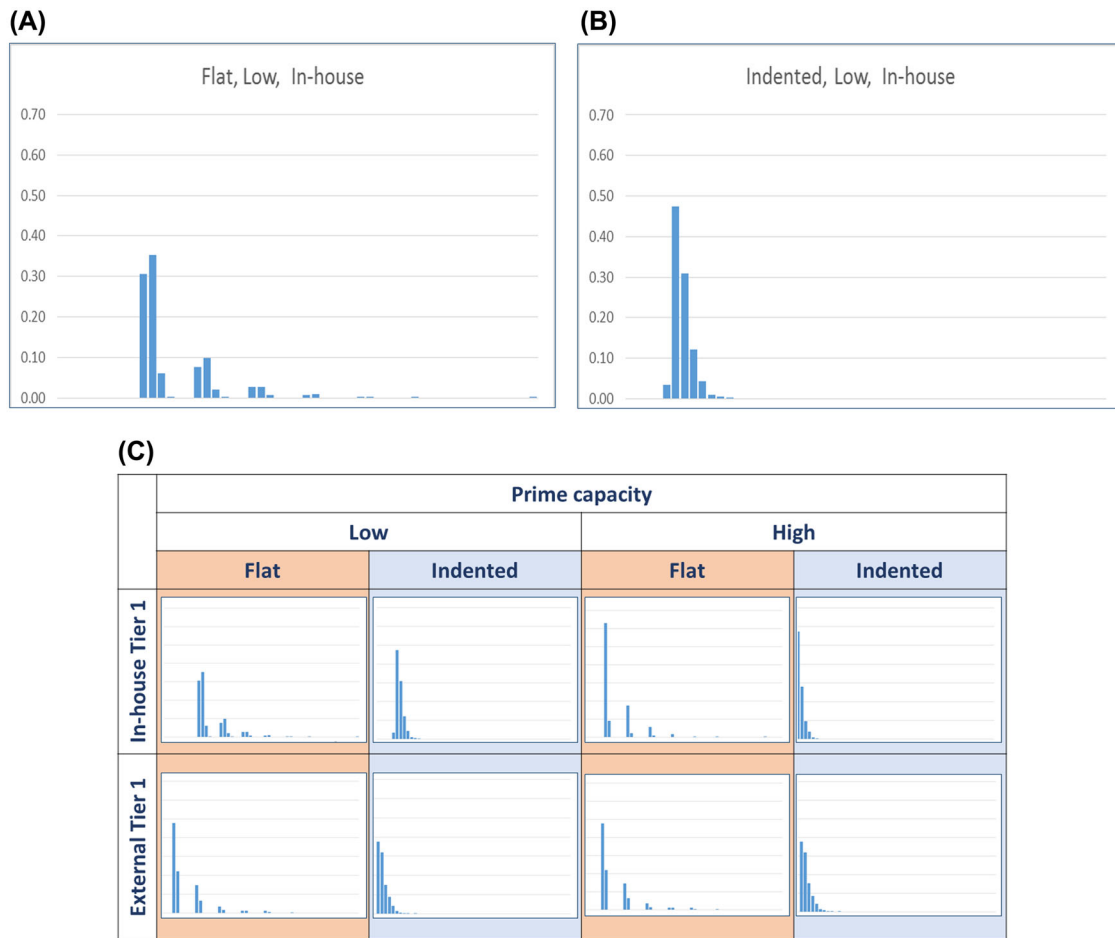


FIGURE 18 Design and make time supply chain risk profiles. (A and B) Detailed views of in-house Tier 1 for flat and indented product structures and low prime capacity; (C) Summary of the eight make-buy scenarios for the case study. (NOTE: In each case, the X-axis is in increments of 40 time units (representing time taken to design and make a test engine), ranging from 60–100 to 1100–1120 and the Y-axis represents the likelihood of a given time taken, ranging from 0 to 0.7 in increments of 0.1.)

relationships such as sub-contracting, where the customer provides the material that the supplier works on, are not covered.

In addition to an appropriately structured and validated model, the quality of the results from any simulation depends on the quality of the data that drives it. For example, any supply chain simulation model needs data related to suppliers and their performance. In this paper the data used to drive the simulations was based on rules of thumb (see Tables 2 and 3) that were applied to all suppliers in the same way. Early in the design process, it is unlikely that specific suppliers will have been identified so the characterisations of suppliers we used were limited to capacity which, in itself, is represented crudely as the number of parallel processes a supplier can carry out. In the software prototype developed as a part of this research, the supplier for each part is specified in a spreadsheet that is generated from the make-buy scenario and can be edited before the simulation model is generated. However, only supplier names, capacities and design and make times for components can be edited. Whether more sophisticated definitions of suppliers are necessary could be a part of future model validation efforts that could

include sensitivity analyses. For example, Gosavi et al.²⁹ provide an approach for understanding risks in the negotiation of contracts with suppliers based on previous experiences of the contracting organization. Similar data could be incorporated into the models reported here and, in the future, approaches such as that reported by Gosavi et al. could be used to generate data for use in our models. An early observation related to the data presented in this paper is that capacity is not always a determining factor. For example, from Figures 18 and 19, it can be seen that the risk profiles for the indented, external make-buy scenarios are not affected by the capacity of the prime contractor. Another factor that affects the performance of the supply chain is the competence of suppliers. In highly regulated sectors such as aerospace, the competence of suppliers is established in supplier selection and development processes. As a result, it is reasonable to assume that all suppliers are fully competent. In other sectors this may not be the case and mechanisms to characterize supplier competence may be needed.

Although intended for designers with limited simulation modelling skills, the simulation models are available to users and could therefore

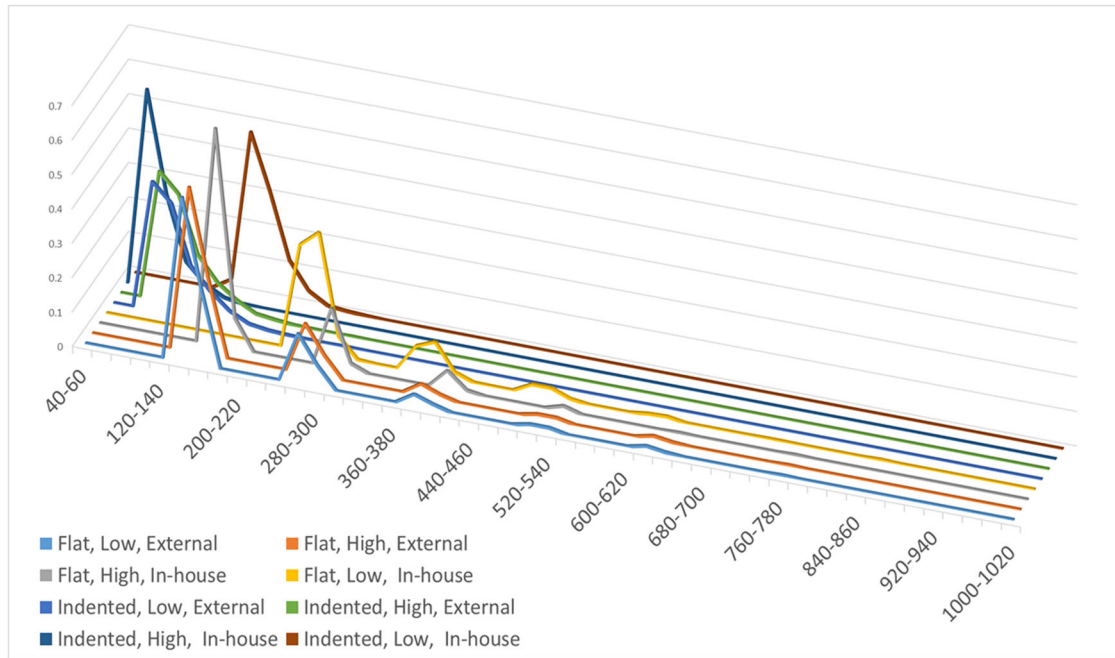


FIGURE 19 Cross-comparison of the eight make-buy scenarios for the parking trolley case study

provide opportunities for deeper analyses of the lifecycle processes included. For example, as discussed earlier, the models can be used to explore root causes of specific phenomena such as relationships between the number of concessions requested and time taken which, in turn, could have wider implications, for example, on organization and supply chain management policies. A caveat for this, however, is that the models introduced here are intended to enable comparisons of design alternatives. If the models were to be used for other purposes then it would be important to ensure that they were adequately validated and that the data on which they were based was appropriate and sufficiently accurate. The overall approach could also be used to generate input data for other kinds of analysis. For example, the application of network science to enterprise architectures introduced by Potts et al.¹³ is driven from a list of organizations that could be generated in the first two steps of our approach (see Sections 4.1 and 4.2) though, again, work would be needed to integrate appropriate data into the model. Similarly, our approach could be used to derive the enterprise architectures needed to drive the analyses proposed by Gokpinar et al.¹⁰ though further work would be needed to incorporate necessary data and their [automotive] vehicle design process. In these and other applications there are opportunities to acquire data through emerging technologies such as digital twins, big data and process mining which could also inform validation methods.

Key drivers for this research were, in an increasingly competitive business environment, (i) the industry need for product development teams to appreciate the supply chain risks associated with early design decisions, and (ii) emerging opportunities for using advanced engineering simulation tools earlier in product development processes. The

granularity of the simulation models derived through the interface is coarser than in typical engineering process simulations, such as those that model the detailed operation of manufacturing processes and are coupled as digital twins with factories where they are used to inform operational interventions. The granularity of the models that can be created is somewhat dependent on the data available (either from collected data or expert opinion) and the level chosen can affect the accuracy and the usefulness of the model which, in turn, depends on its intended purpose and resources available to build and use it. In the future, when the use of such tools is an integral part of product development processes, supply chain models could form the basis of more elaborate simulations, for use later in the product development process. For example, models linked to supply chain operations could be used to both inform those operations and collect data to improve the veracity of the models used in future development processes. In supporting later, detailed design stages of the product development cycle, factors to enable the estimation of costs and variables such as product volumes are likely to be required and approaches such as the one introduced here might assist simulation professionals by providing skeletal models that could underpin purpose-built simulation models.

7 | CONCLUSIONS

Experience of working on design programs across global supply chains highlights the importance of design engineers appreciating the consequences of design decisions for supply chain operations. This is especially important in highly regulated sectors, such as aerospace,

where the regulatory environment holds the chief engineer accountable for decisions made in the design function. Typically, however, design engineers are not involved in the day-to-day operation of the supply chain and so do not have a detailed appreciation of the complexities therein or the ways in which design decisions (e.g., related to product architectures, configuration management and change control) lead to supply chain risk. This creates a need for methods and tools that can be used by design engineering teams to better understand how design decisions might affect supply chain flows. Such tools have the potential to enable the early identification and assessment of supply chain risks. Further, given the time and cost pressures under which design teams operate, such tools need to be suitable for use by design engineers who are not supply chain specialists.

In this paper we have demonstrated the feasibility of such tools by deriving simulation models of design and make supply chain processes from the product architectures that are developed in preliminary design processes. Results from these models can be used to inform early design trade-offs related to product architectures and make-buy decisions when the [financial and time] costs of change are at their lowest and the potential for innovation is at its highest. By their very nature, the simulation models generated using the approach introduced in this paper lack the detail that would be needed to allow the identification of all so-called “unknown unknowns” that create risks through the entire lifecycle of the product. For example, they do not contain sufficient information to inform long term decisions related to supply chain logistics or accurate cost estimation, and some factors affecting lifecycle processes, such as new regulations surrounding net zero and other sustainable development goals, are not yet in place. Instead, the value that the simulation models provide is additional information for decision makers to enable the early identification of design and make supply chain risks related to the design of product architectures, and so decisions surrounding how these risks are to be managed or whether these risks need to be removed or reduced through changes to the design.

To be used in real world preliminary design processes, however, further work is needed to ensure that (a) the simulation models are adequately validated for their specific contexts of use, and (b) the cost of use (e.g., additional user training and effort) is proportionate to the added value created. With respect to model validation, in this paper, the choice of process (the development of test products for certification) and performance indicator (time taken in design and make supply networks), made it feasible to access necessary data. Early work exploring the applicability of the approach to the construction sector³⁰ has also highlighted the importance of incorporating factors from the business operating environment that influence process operations, especially when the processes are operated by multiple organizations in more volatile supply chain contexts. The approach could also be adapted to support simulations of other lifecycle processes. However, new process metrics and further data would be needed, and so further work to integrate these into the process simulations. For example, in principle, the approach could be used to compare design alternatives in terms of their carbon footprints but this would need details of the

lifecycle process being considered, and data on carbon footprints that may not be available and could be affected by wider factors such as the behaviors of users. With respect to cost of use, the interface (including data input and presentation of results) uses Excel which is widely used in the engineering design community. The input data is in the form of an indented parts list annotated with make-buy data. Indented parts lists are a widely used format but the annotation with make-buy data is additional information that needs to be added. In the case study used in this paper this data was added manually. In a full implementation this could be partially automated. For example, it would be straightforward for a competent programmer to write Macros that annotated the BoM using rules of thumb such as that given in Table 5. In summary, given adequately validated simulation models, the cost of use has the potential to be low in the light of the added value from the use of such tools in enabling the early identification of supply network risks and so trade-offs that may need to be considered in later stages of the product development process. As outlined in the Introduction to this paper, the approach presented in this paper is intended for use early in the product development cycle as part of preliminary design. A key strength of the approach lies in its focus on specific design alternatives which gives design engineers opportunities to experiment with alternative product structures and make-buy scenarios early in the design process. To be used in real-world product development processes, however, further work is needed to ensure that such tools are integrated with wider perspectives than those of engineering design. For example, Olivares Aguila and ElMaraghy³¹ provide a framework for the assessment of the topological characteristics of supply networks and so their complexity and robustness that could be used as an additional analysis tool to complement the simulations we produce in our research and Ülkü and Schmidt³² consider wider business drivers, such as market characteristics, that need to be considered in the development of product architectures.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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Alison McKay received a BEng (Hons) in Mechanical Engineering from the University of Bradford in 1982. After a period in industry she joined University of Leeds, in 1984, as a research engineer and was awarded a PhD on relationships in product data in 1996. She is a chartered engineer and a Fellow of the Institution of Mechanical Engineers. Her research centers on **socio-technical** aspects of engineering design systems and the networks of organizations that both develop and deliver products to market, and support them through life to disposal or reuse. The focus of her personal research lies in the establishment of systematic and, where possible, well-founded underpinnings for such systems, in particular, for the definition of product data. This has led to research on extended enterprise network structures and their alignment with the delivery of business

strategy. Her research is positioned within the context of stage gate processes that typify current industry practice. It aims to facilitate improved modes of working through the exploitation of digital technologies and to establish design methods and tools to support systematic evaluation of design alternatives at decision gates.



Dr. Richard Chittenden has worked in the School of Mechanical Engineering since completing BSc and then doctoral thesis on "The Elastohydrodynamic Lubrication of Elliptical Contacts" in 1984, for which he was awarded the IMechE Bronze Medal for tribology. Initially, this was as

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Thomas A. Hazlehurst is a Postdoctoral Research Fellow at the School of Mechanical Engineering at the University of Leeds, UK. He holds an undergraduate degree in Mathematics (2011) and a Ph.D. in Applied Mathematics (2015), both from also from the University of Leeds. Since gaining his

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Alan de Pennington is an Emeritus Professor at the University of Leeds. He gained his BSc in Mechanical Engineering, MSc in Control Systems Engineering and PhD from the University of Manchester. He joined the Philips Research Laboratories in Eindhoven in 1970. He was appointed as a Lecturer at the University of Leeds in 1972 and Professor of Computer Aided Engineering in 1984. In 1986 he was seconded to the National Science Foundation in Washington DC as the Program

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Richard Baker is a Visiting Professor at the University of Leeds, having been awarded a Royal Academy of Engineering Visiting Professorship in 2015. He is an Incorporated Engineer and a Fellow of the Institution of Engineering and Technology. Richard supports the School of Mechanical Engineering providing technical knowledge and experience

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Tony Waller received a BSc (Hons) in Statistics from the University of St. Andrews in 1981 and has worked in the field of Operational Research and particularly simulation ever since. He has worked on many diverse international assignments as a consultant and has

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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