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A FRAMEWORK FOR STUDENTS TO VISUALISE THE IMPLICATIONS OF DESIGN DECISIONS IN GLOBAL SUPPLY NETWORKS

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ABSTRACT
Engineering innovation is recognised as a key to business success. Transitions to new business models, including Design & Make supply networks and through-life support services such as the Rolls-Royce TotalCare® package are creating new kinds of innovation opportunities through entire supply networks. Engineering and other graduates need improved supply chain awareness and skills to operate effectively in these emerging innovation contexts. In contrast, the coverage of practical supply chain issues in universities' engineering curricula tends to be limited. Reasons for this include limited access to industrialists with practical supply chain experience and limited linkage to research which is largely carried out in business schools, with a focus on the firm, rather than the focus on products, services and associated innovation processes that are more relevant to engineers. This paper introduces a pragmatic framework that has been designed to raise awareness in engineering undergraduates of where engineering innovation happens in global supply networks and how the behaviour of individual organisations impacts overall network performance.

Keywords: Systems design vee, discrete event simulation, design & make networks, innovation

1 INTRODUCTION
The systems engineering vee model provides a structure for the development of large, complex products such as aero-engines. This model, along with the system architecture that results from its application to an initial capability statement, governs the structure of both the product and the supply network used to design, produce and support the product through life [1]. The systems engineering vee is widely used in industries that employ large numbers of engineering graduates. However, a detailed analysis of systems engineering processes reveals (i) there are many editions of the vee model, each with its own nuances and features, and (ii) current models tend to concentrate design on the left-hand side of the vee and product realisation on the right-hand side of the vee. As a result, it is not possible for engineering and design students to experience the process in undergraduate courses because universities do not have access to the necessary product realisation facilities and students do not have the time or design and manufacturing capabilities needed to use them effectively. This paper introduces an educational framework that addresses these issues by developing the left-hand side of the vee into a so-called "systems design vee model" and using discrete event simulation software to explore implications of design decisions without needing product realisation facilities.
The framework brings together design theory and industry practice. The key aspect of design theory is the zig-zagging design process between functional and physical domains [2]. From industry practice, the framework allows students to create design descriptions that inform the flow down of requirements through the supply network and make-buy decisions. A brief review of background literature in these areas is provided in Section 2. The framework itself is introduced in Section 3 and an application that couples a design process case study with discrete event simulation tools to give visualisations of potential design networks is presented in Sections 4 and 5. Finally, in Section 6, key learning from the creation and early use of the framework are discussed and areas for future work outlined.

2 BACKGROUND

The discipline of supply chain management has existed for over fifty years and the generic cross-organisation processes that influence supply chain operations are well understood and supported by ubiquitous computer systems such as MRP and ERP. For student education, there is a range of educational tools, such as business games based on roleplay[1] and associated software simulations, which provide students with insights on and experience of the principles of supply chain management. These tools exploit three key features of supply chains: (i) physical parts flow through the network in large volumes from suppliers to customers; (ii) the performance of a supply chain can be quantified in terms of the correct number of products being delivered to the customer in a specified timescale (often referred to as "OTIF - On Time, In Full"); and (iii) the limiting factor for achieving OTIF is capacity in the supply base. Design networks, a more recent phenomenon, are used to develop innovative new products [3]. Unlike supply chains, information, in the form of technical data packages [4] and design requirements [5], flows between customers and suppliers [6]. In addition, ways in which the performance of design networks might be quantified is the subject of research and the key limiting factor in the operation of a design network lies in the design capability (as opposed to the capacity) of the supply base [7, 8]. As a result, tools used in supply chain education are not well suited to design. The educational challenge addressed in this paper can be summarised in the question, "How can we prepare students to work in and manage design networks?"

For the manufacture of a large, complex products such as aero-engines, the systems engineering vee provides a framework that determines the structure of the supply network. The "systems design vee" model introduced in this paper has the same form as a traditional systems engineering vee but produces designs rather than manufactured solutions. Figure 1 illustrates the systems design vee and how it relates to the vee model introduced in [9]. It can be seen that the left-hand side of the model captures functional information related to system and subsystem (which themselves are systems) requirements and the right-hand side relates to design solutions in the form of system and subsystem architectures. In addition to its alignment with industrial systems engineering practice, the systems design vee aligns with design theories and processes that form a core part of many engineering design curricula [2, 10]. Specifically, the explicit separation of design requirements and solutions aligns with Suh's functional and physical domains, and supports the zigzagging process between the domains that Suh recommends and which forms the basis of design iteration in design processes.

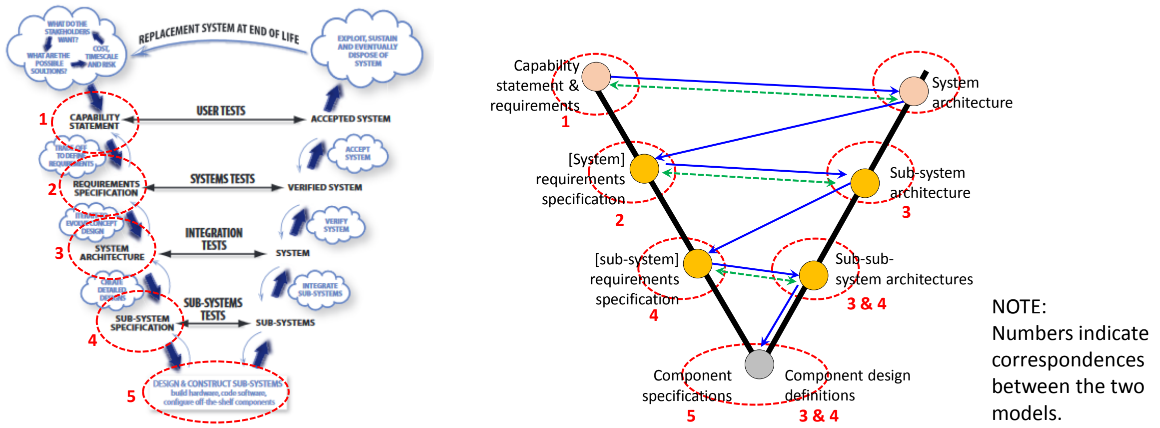


Figure 1. RAEng vee model (reproduced from [9]) and the systems design vee

3 THE SYSTEMS DESIGN VEE & ITS APPLICATION TO DESIGN NETWORKS

The development of the framework is part of a wider project whose goal is to bring design and supply chain thinking and practice into engineering curricula. As part of this project, the authors have been

[1] For example, the widely used Beer Game http://www.beergame.org/the-game

working with engineering students on the development of diagnostic toolsets[2] for the measurement of supplier organisations' design innovation competence and capability. The development of such tools requires an understanding of cross-organisation engineering design processes and flows that occur within design networks. Both supply and design networks operate in two modes: flow down of requirements to suppliers (order volumes and due dates for supply chains and technical requirements in design networks) and flow back of responses to these requirements to customers (parts in supply chains and design descriptions, in the form of technical data packages (TDPs), in design networks). The framework introduced in this paper reflects these two modes of operation, as shown in Figure 2(a) and (b), for design networks.

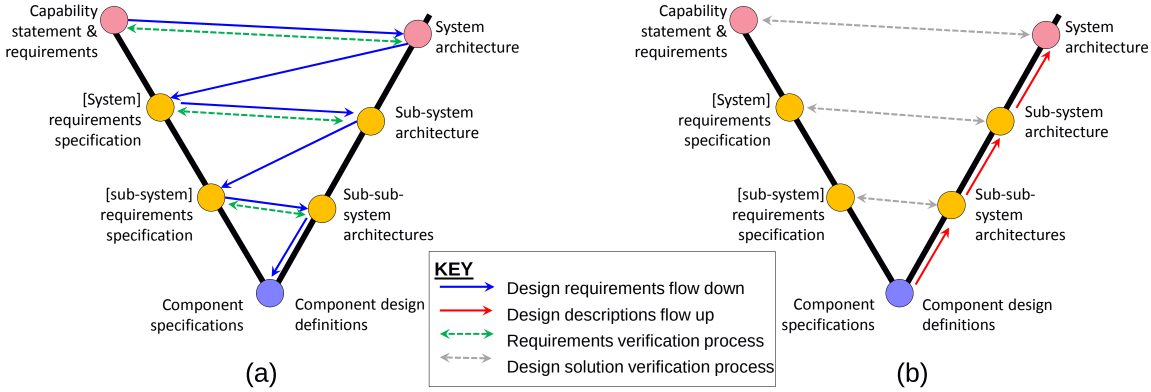


Figure 2. (a) Flow down and verification of requirements, (b) Flow up and verification of design solutions

Figure 2(a) illustrates the development and verification of design requirements, starting in the top left-hand corner of the vee with the flow down of design requirements shown by solid (blue) arrows. These arrows zig-zag between the functional and physical domains because the requirements for parts [sub-systems] of a given system depend on the overall system architecture. For example, in the design of a car, whether it has an automatic or manual transmission affects which sub-systems are needed and what is required of them. Before architectures and requirements are confirmed for any element of a design, a design verification process, shown by the dashed (green) lines, takes place. In this process, alternative requirement envelopes for different parts of the system are considered and make-buy decisions made and approved through series of design reviews. These make-buy decisions, coupled with the system architecture, determine the structure of the design network. Figure 2(b) illustrates the development and verification of design solutions. This starts at the bottom of the vee, with the design of components, followed by their integration into sub-systems and, ultimately, the whole system. The flow up of solutions is shown by solid (red) arrows in Figure 2(b). Design iteration occurs within the design processes for each component and across the vee through the design verification process, shown by the dashed (grey) lines, where solutions are verified in design reviews. For clarity, Figure 2 shows the process for a system decomposed into sub-systems that are collections of components; in practice the number of levels of decomposition can be varied to reflect the system being designed.

Visualising design networks requires process simulation which, in turn, requires understanding of the processes carried out across the network. The framework in Figure 2 can be used to derive such a process, as shown in Figure 3 where the two aspects of the framework are expanded into a series of process steps. The diamonds in Figure 3 show stage gates in the system design process that emerge when the framework is applied to a specific design problem. As shown in the next section, the process itself is variable because its makeup depends on the structure of the design that is embedded in the system and sub-system architectures.

[2] Where it was anticipated that such toolsets will include a flowchart to define the assessment process, supply chain simulation models for use in the context of this process to visualise the health of at least one supply chain, and supply chain scenarios that can be used to demonstrate the potential of the simulation models.

4 CASE STUDY

The case study used in this paper is the simple system architecture shown in Figure 4(a), which, if the design of all parts was outsourced (Scenario 1 in Figure 4(b)), would result in the design network structure shown in Figure 4(c). The processes that result from applying the framework to each of the scenarios in Figure 4(b) are shown in Figure 5 and Figure 6 respectively. As shown in Figure 6, in Scenario 2, all B-co and C-co design work from Scenario 1 is carried out by A-co. This increases the scale and complexity of A-co's work but reduces the size of and simplifies the design network and associated cross-network processes.

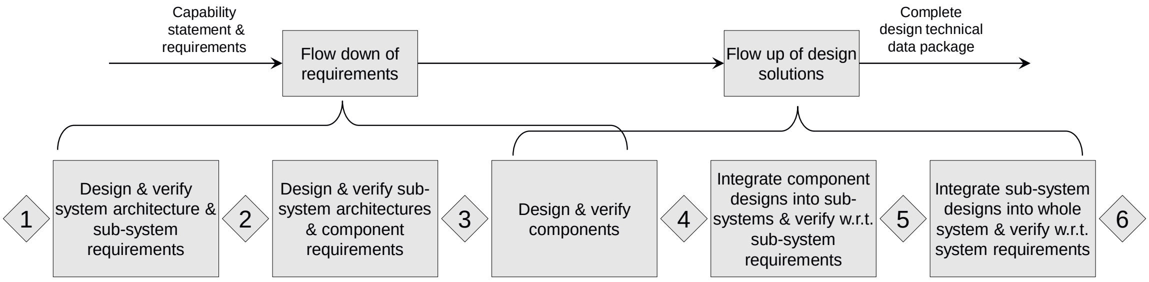
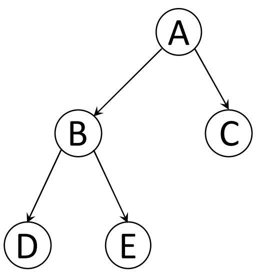


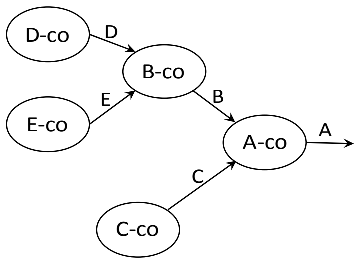
Figure 3. Derived process for a system with one level of sub-systems and components (NOTE: In practice, the length of the process grows with the number of levels of system/sub-system decomposition increases)



(a)

	Make Buy Decisions			
	Scenario 1		**Scenario 2**	
Part	**Design**	**Make**	**Design**	**Make**
A	Internal	Internal	Internal	Internal
B	External	External	Internal	Internal
C	External	External	Internal	External
D	External	External	External	External
E	External	External	External	External

(b)



(c)

Figure 4. (a) Product structure; (b) make-buy scenarios; (c) network structure for Scenario 1

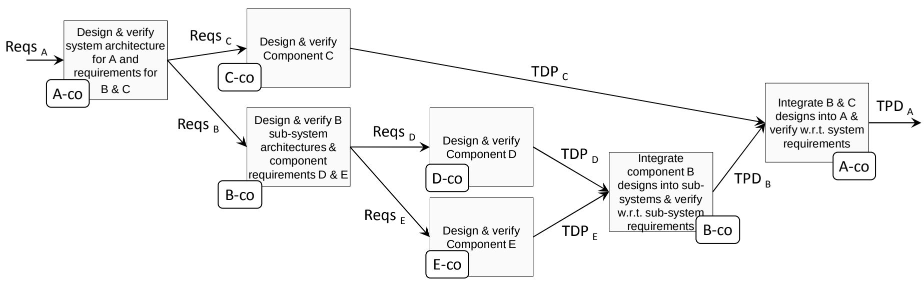
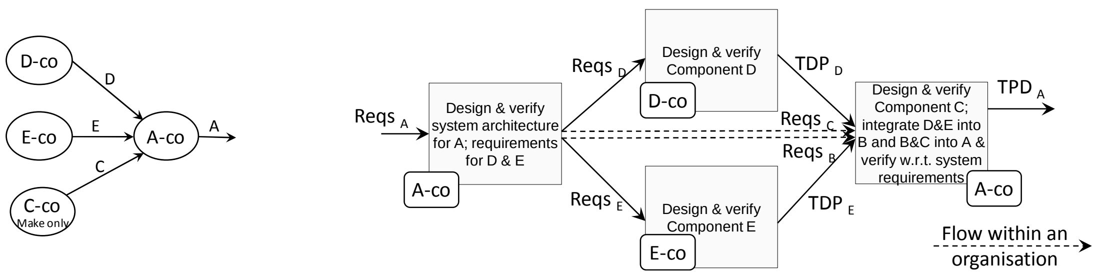


Figure 5. Scenario 1 cross-network design process (stage gates omitted for clarity)



(a) (b)

Figure 6. (a) Scenario 2 network, and (b) cross-network design process (stage gates omitted for clarity)

For this paper we use acceptance for the next process stage at a stage gate as a proxy for time risk in the network. 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. For the simulations, this was quantified by allocating the likelihoods shown in Table 1 of passing through each gate and, if not; likelihoods of rework were being needed by previous stages. In addition, this table shows assumptions made for the times taken for each element of the process.

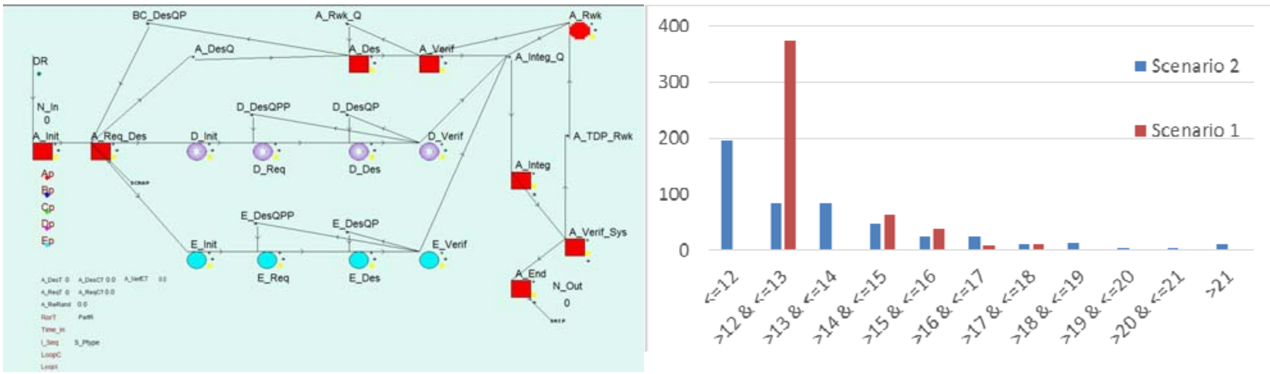
Table 1. Time taken and uncertainties in the network process

Time used per subsystem or component	Time units
Each input to a process adds	0.50
Each system design activity takes	0.67
Each component design activity takes	1.00
Each verify activity takes	0.33
Each system integration activity takes	0.67
Each output from a process adds	0.50

No. of stages back		A	B	C	D	E
Requirements need rework	One	n/a	15%	10%	10%	10%
	Two	n/a	n/a	n/a	5%	5%
	Three	n/a	n/a	n/a	n/a	n/a
Technical Data Package needs rework	One	15%	10%	n/a	n/a	n/a
	Two	10%	3%	n/a	n/a	n/a
	Three	5%	3%	n/a	n/a	n/a

5 SIMULATIONS

The processes in Figures 5 and 6 were implemented in the Witness simulation package; as an example, Figure 7(a) shows the process that was implemented for Figure 6. In both cases a number of accommodations were needed for each step in the process. These are the nodes in Figure 7(a) that end in 'rework' and 'init'. The 'init' steps are needed to enable the control of flows into the process step, and so its initiation and that of subsequent steps, and the 'rework' steps are needed to direct rework to the correct process step. The simulation models also highlighted some ambiguities in the models. For example, when rework moves one step back from 'A' there are two steps to which it can be directed.



(a) (b)

Figure 7. (a) Implementation of the Scenario 2 process from Figure 6 in the Witness simulation package; (b) times taken running the model 500 times for each scenario

The model shown in Figure 7(a), which without any randomness or loops had a base time of 11.3 time units, and the implementation of the process shown in Figure 5 were attributed with data from Table 1 and run 500 times each. This resulted in the distribution of process times shown in Figure 7(b).

6 DISCUSSION & CONCLUSIONS

The approach introduced in this paper provides a means by which process maps for the design and development of a given design can be derived. The availability of such maps gives students a concrete means by which they can apply systems engineering principles, especially in the flow down of requirements and the verification and validation of design proposals. In our work to date, students have produced process maps for design case studies and used them to inform to development of supply chain operation models that give practical insights into consequences of early design decisions on supply and innovation network processes and so downstream risks in product development processes. Given product architecture and decisions on whether or not subsystems and component parts are to be designed and/or made in house, we have shown how supply network processes can be visualised using process simulations.

The longer term potential of this work is for new kinds of design tool that enable consideration of downstream implications of design decisions early in the design process when crucial trade-offs are made. We have demonstrated this potential through process simulations where risks are quantified with respect the time they add to the overall process. Key data used to drive these simulations are the times needed for each activity in the process and the risk of rework that extends the overall time taken. Such data is often inaccessible, especially in networks of organisations that may be collaborating in some contexts and competing in others; in this paper estimates were made to demonstrate the feasibility of the approach. The simulation model itself represents the likelihood of rework as an attribute of verification processes. There are other ways to model this and in supply networks, where supplier capability and relationships within the network affect overall performance, another option is to introduce uncertainty in the nodes and arcs of the simulation model. Now that the framework has been established, our plan is to explore different modelling options in future work.

Further work is also needed to collect data to drive the simulations. The simulation results have been face validated as representative of what might happen in practice but further work is needed to collect data that would be needed to drive more realistic simulations. This is likely to be challenging in industrial situations, where there are many complexities [11], such as Fine’s proximities that are attributes of both organisations and relationships between them [1], and different organisational capabilities and capacities. However, emerging data sciences may provide opportunities for advanced data collection in such circumstances. A further challenge, especially in design and innovation networks, lies in identifying parameters that are critical to quality. From initial explorations in this area, considering design deliverables and root causes of non-conformances in aerospace design processes, a further challenge will lie in quantifying critical attributes in ways that are suitable for the simulations.

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