12TH INTERNATIONAL DEPENDENCY AND STRUCTURE MODELLING CONFERENCE, DSM'10
22 – 23 JULY 2010, CAMBRIDGE, UK

USING CONNECTIVITY MODELS TO SUPPORT DESIGN REVIEWS

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Keywords: design structure matrix, design interface management, design review

1 INTRODUCTION

Design reviews are vital to the development of any product as a failure to identify potential problems early in the design process could have severe consequences on product quality, cost and schedule. In practice, a wide range of issues influences the design review process affecting what actions are taken to deliver a product. Examples of such issues include the complexity of the product and the duration of the product development cycle, the effectiveness of collaboration with project partners and suppliers, and in some cases language differences or geographical locations of key stakeholders in the review process (Yadav et al. 2007). In order to enhance the effectiveness of a design review, it is important to support effective communication between participants (Maier et al. 2009). Given that complex products are developed by multi-disciplinary teams, having a detailed overview of interactions between systems which make up a product is vital (Bucciarelli 1988).

Connectivity models were developed as a simplified way of representing complex ranges of interactions within complex products (Jarratt et al. 2004). The model captures different interactions between the components of a complex product and visual representation of a Design Structure Matrix. In a study to understand where problems lay in engineering change processes in a diesel manufacturing company, Jarratt et al. (2004) observed nobody had an in-depth understanding of all aspects of a modern complex product. They also learned that building connectivity models is a valuable learning experience as model builders became increasingly aware of other technical areas in a product. They argued that identifying component linkages using a connectivity model could help gain an overview of interactions within a product.

In this research, a qualitative investigation was carried out to assess the value of using connectivity models in design reviews. The study looked into the use of the model by multi-disciplinary teams during the design of rail vehicles. A variation of the connectivity model was provided to design teams as a memory aid to support their design review meetings at different stages of a design process. This research is essentially a use case scenario study of connectivity modelling in industry. Consequently attention was placed on the value of its usage as opposed to previous studies which either looked at the value in building connectivity models (Jarratt et al. 2004) or how product architectures may be improved as a result of better elicitation of component dependencies (Pimmler and Eppinger 1994; Baldwin and Clark 2000).

The next section provides a brief discussion on the objectives and challenges of carrying out design reviews. It also describes the overall methodology adopted for conducting this research. This section is followed by a description of the adaptation of connectivity models to modelling interfaces of rail vehicles. The following section describes an application of the connectivity models to design reviews. The paper concludes with a summary of the merits observed from the study and a discussion about the challenges associated with rolling-out the approach to other areas of the organisation.

2 BACKGROUND

Design problems can arise at any stage of a design – from concept to detailed design. Seemingly innocuous problems can be difficult to spot early in the design process and expensive to fix as the design matures (Eckert et al. 2004). Design reviews help engineers to think through the workings of a product and identify problems that may arise in the design. However, the actual process and degree of formality may vary from one organisation to the next.

Reviews may involve participants from different disciplines or environments collaborating. In what Bucciarelli (1988) terms as "object worlds," design engineers' perceptions of objects are influenced by their technical backgrounds. Thermal specialists consider attributes of an object, which are different to those observed by structural specialists, yet they refer to the same entity. Irrespective of the approach taken, a lack of a sufficient overview of component interactions can undermine the effectiveness of communication and consequently the success of a design review.

2.1 Design and interface matrices

The DSM has identical rows and column labels and has been described in detail in various published articles. It is an efficient method for representing dense interactions between corresponding entities. Browning (2001) provide a review of DSM methods and applications in various fields of research including product architectural dependencies, process task dependencies, information flow and organisational structures.

Variants of the product DSM are reported in design literature. One of the early attempts to model products in terms of their component interfaces was presented by Sosa et al. (2003), who identified five types of dependencies, spatial, structural, energy, material and information within a jet engine based on another study conducted by Pimmler and Eppinger (1994). Sosa et al. (2003) called the model a Design Interface Matrix (DIM). It is important that this DIM model is not confused with another type of Design Interface Matrix presented by Senthilkumar and Varghese (2008) which attempts to map components to disciplines or the Interface Structure Matrix presented by Kusiak (2008) which is intended to map components to tasks. Of the different dependency modelling techniques discussed, the Design Interface Matrix presented by Sosa et al. (2003) draws on the strength of the DSM and provides a concise way of representing dense component interactions. The model in this study is a variant of the Sosa et al. (2003) Design Interface Matrix.

2.2 Methodology

The study was carried out in close collaboration with a rail vehicle manufacturer. First a connectivity model of a rail vehicle was developed. This helped to provide an overview of the interacting systems within the vehicle. Second, the connectivity model was used to support the design review process. Three users of the process were subsequently interviewed to identify advantages and drawbacks of using connectivity models in review meetings. Further background information was gathered from the manager and the engineers involved in the application of the DSM.

3 DEVELOPING A CONNECTIVY MODEL OF A RAIL VEHICLE

A study looking into the use of connectivity models was carried out in a UK based division of a multinational engineering company specialising in the manufacture of civil aerospace planes and rail vehicles. The manager responsible for engineering process improvement within the company initiated the pilot after learning about another study which looked into connectivity modelling and change prediction (Clarkson et al. 2004) within the Oil & Gas industry. Both the model building exercise and the facilitation of design reviews were carried out by staff of the organisation. Guidance on how to build models and interviews to assess the usefulness of completed and augmented models were carried out by the second and first authors respectively. As the aim was to pilot the method within the company, it was decided to use available spreadsheet software instead of specific DSM software.

3.1 The challenge to developing a new product

Each design of a rail vehicle is developed to customer requirements for various daily applications. The study looked at the use of a connectivity matrix to support the development of a rail vehicle intended to serve on one of the London or South East England rail networks. The project was particularly challenging because the total development cycle was to be carried out in half the usual time for projects of similar magnitude within the organisation. The total time allocated for the project was one year. Given the unusual time pressure, the teams were willing to try out new methods which could help identify and minimise errors during the design process.

The design of a new train begins with an evolution of an existing design. This practice is not uncommon in practice. Nichols (1990) explained that new models of Japanese cars contained only 40-

60% new design content. Design reviews are focused at three main gateways in the design process including conceptual design, preliminary design and detailed design. Design engineers compile a list of the changes from the base product and proceed to look for clashes in the design within systems that are expected to remain unchanged and across newly designed systems. Geometric clashes may be identified using CAD packages but these do not identify the knock-on effects of design modifications on the performance of components.

Challenges to resolving clashes between components arise from a number of sources. To help improve understanding on how to resolve such clashes, it is important to realise that there are many engineers grouped into functional teams involved in the development of the train. Interviews with four engineers helped discern some of the main challenges to identifying and resolving clashes in the organisation. Some of the key challenges in achieving a detailed and robust review were:

1. *Need for overview*: a component interface with multiple systems within a product. Potential clashes between parts of a product are resolved by engineers responsible for specific components in the product or disciplines. By focusing on issues surrounding a component from a single discipline, other interactions to other components within the product may be overlooked.
2. *Need to minimise disruptions arising from design errors*: Design reviews are guided by experienced engineers to minimise errors but should a design error go unnoticed during design reviews, it could lead to disruptions in work flow and even redesign of components. It is important that all relevant disciplines are represented at design review meetings.
3. *Need for review progress monitoring*: There are interface control documents in place which point to all interfaces in the design that should be evaluated but there is a need for representations to enable quick accessing of relevant interfaces and techniques for explicit monitoring to review progress on already resolved clashes. As a result, there is an opportunity to improve the process.

3.2 Model building

Contributions to an initial model of component connectivity were provided by 12 Engineering Specialists from within the organisation. The modelling exercise began with an identification of a suitable level of granularity to describe the rail vehicle. The product decomposition was derived using a *global standard product structure* available within the organisation. The level of detail was chosen so as to enable a manual population of connectivity models. Product DSMs reported in design literature consist of approximately 40 systems and components. A product breakdown of 76 elements was derived for connectivity modelling in this study.

The objective of the connectivity modelling was to identify what types of links exist between components and the strength of their interactions. There were three forms of component linkages identified. Each type of link was ranked using qualitative indicators of the strength of interactions between component pairs. Table 1 shows details of the interface types considered during connectivity modelling.

Table 1. Criteria for populating connectivity model of rail vehicle interfaces

Interface types	**Interface definition**	**Interface strength ranking**
Spatial	Component and assemblies are identified as having a spatial interference connectivity if a change to the element along a column encroaches in the space envelope for a component in the adjacent row. This includes space for normal operation, installation, removal of access covers, etc.	Minor: Minor spatial interference.
		Major: Multiple spatial interface
Geometric	Component and assemblies are identified as having a geometric connectivity if a change to the component in the column had a physical interface with one or more components in adjacent rows.	Minor: Simple bolted joint or welded fastening
		Major: complex joints or multiple fastenings

Interface types	Interface definition	Interface strength ranking
Functional	Component and assemblies are identified as having a functional interface if a change to the component in the column has a direct effect on the function of the component in adjacent rows	Minor: Components interface via static load
		Medium: Components have simple dynamic interface e.g. moving connection
		Major: Components with complex dynamic or complex electronic control interface

Using the company's standard product breakdown structure and the interfaces listed on Table 1 above, a connectivity model was created. It was necessary to decentralise the effort used in filling out the matrix. Consequently, the blank matrix was populated in two stages. First the model was primed by the facilitator with the assistance of engineers within the organisation drawing on information from CAD drawings and other documents. The connectivity model was built following guidelines described in Jarratt et al. (2004).

All interfaces with the exception of functional interfaces were allocated a score of 1 and 2 for minor and major respectively. Functional interfaces were allocated scores 1, 2 and 3 for minor, medium and major interference. An estimate of the strength of interference between two component interfaces was derived by summing all the scores for the spatial, geometrical and functional interferences.

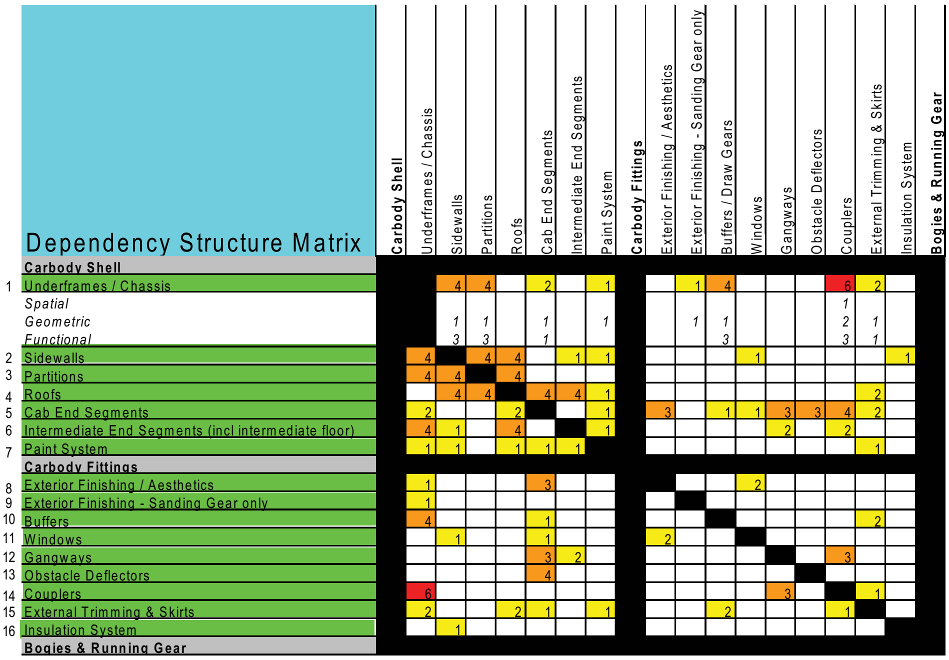

Figure 1. A section of the product interface connectivity model for a rail vehicle

A section of the connectivity model consisting of 16 of all 76 components and assemblies is illustrated in Figure 1. The diagram also shows an example of the scoring for *spatial, geometric* and *functional* dependencies (see *underframes/chassis*). The total score per relationship is given by adding up the individual assessments for all three forms of interaction. The model helped to identify high interference interfaces between components in the rail vehicle. In addition to the scores, comments were attached to each cell to reflect the thinking about the relationship at the time the model was built. An example of a comment between *sidewalls* and *roofs* shown in Figure 1 is "Sidewalls supports roof; roof fastened to sidewalls."

4 DISCUSSION ON SUPPORTING DESIGN REVIEWS

The connectivity model has since been used to support both pre-design review and design review meetings. The DSM was used to structure the discussion and review during the meeting and displayed on a large screen in the meeting room. Typically ten engineers from various disciplines normally take part in the meeting. The review followed along the row of a particular sub-system or component. By reviewing each interface, design engineers discussed in detail the challenges to achieving the requirements specified for such interfaces. All interfaces were reviewed irrespective of the scores within the connectivity model.

One engineer explained that no single individual had a complete overview of the different types of interactions between all components. Sometimes it was not immediately clear why a link was identified in the model. A quick review of the comments attached to each cell helped to determine the nature of the relationship.

Early results suggest that connectivity models offer a variety of benefits. The study verified one of the key claims from an earlier study looking into the use of connectivity models to manage linkages within diesel engines (Jarratt et al. 2004). By providing an overview of component interfaces, the study showed that the model does act as a memory aid which draws attention to all interfaces concerning components under review.

Examples of comments made by senior engineers, extracted from the study transcripts, give an indication of the usefulness of the technique as a memory aid*: "Before it* [i.e. the review of design interfaces] *relied a great deal on the knowledge and experiences of the engineers […]. But for the best will, something is due and gets forgotten or overlooked."[…] It* [i.e. the connectivity model] *allows us to have a far more detailed and robust design review process because obviously interfaces are a massive part of design. It allows us to finalize designs earlier and have confidence that interfaces have been reviewed and checked."* However, there was no evidence that building the model helped team learning. This can be explained by the decentralised approach to model building adopted for this study as opposed to the team centric approach used by Jarratt et al. (2004).

Aside from validating findings from Jarrett et al. (2004), the study gave new insights on the merits of using connectivity models. The engineers argued that the models reduce disruption in the work flow. System engineers were able to concentrate on completing their work schedule without being called upon to address unplanned activities such as the erosion of tolerances between interacting systems. As one team leader stated "*Because if we have issues [...] then that comes straight back to me or say back to us as a team. For the relevant system engineer, everything else he is doing is put aside and he concentrates on that until the [issue is resolved]. And that's the impact it has."*

The benefits to daily design operations extend beyond reduction of rework to include planning of review meetings. The use of connectivity models to support pre-design review meetings enables identification of the disciplines affected by any proposals for design modifications. Consequently, it helps to set an agenda for review meetings as well as inform decisions as to which stakeholders should be present. At the time the study was conducted, it was not possible to associate an objective value to the gains made using connectivity models.

In summary, the connectivity model of component interfaces enables the engineering team to identify the critical areas concerning system interfaces and steers the design review to focus on these key areas. The true benefit of using connectivity models to support the design process will only be experienced once the first vehicle build is completed. The company is expecting a reduction in non conformity cost and engineering changes associated with system interfaces. Measures such as the number of hours saved as a result of using connectivity models are to be considered in future research.

4.1 Model and research limitations

The connectivity model is not without its weaknesses. This study uncovered a number of limitations relating to how models are built as well as its utility. The most significant challenge to building models was obtaining a consensus on the nature of interaction at interfaces and the estimates of their strength. Engineers tasked with validating the columns of the connectivity had an inconsistent interpretation for each type of interface. Similarly, it was difficult to assign scores to the strength of interactions at each interface. Many engineers make such judgements based on their operating experience. A component interface interference, which may otherwise have been considered minor by the facilitator, may be scored major by another engineer. This is especially the case when such interface has led to a problem on a previous occasion.

The final limitation to the use of the connectivity model observed during the study concerns the issues of visualisation. The connectivity model was built using a spreadsheet. The engineers explained that they found it easier to interact with the model once it was projected on large screens or printed on large paper (e.g. A0 size). They argued that in situations where the connectivity model was accessed on devices with considerable small screen spaces, interacting with the model became difficult.

5 CONCLUSION AND FUTURE WORK

This paper has described a study looking into the use of connectivity models as a way of supporting design reviews during the development of a rail vehicle. It was argued they offer a number of vital operational benefits to design engineers involved in the review process. The connectivity model was used as a memory aid since it provides a simple, yet effective overview of the product. This helps to set an agenda for review meetings as component interfaces which might be affected by modifying a design can be readily identified. The use of connectivity models in design reviews can add to the robustness of the review process. By preventing failures to identify interacting interfaces, the implication of the new practice is that disruptions in day-to-day workflow can be minimised.

Research is currently being carried out to enhance the current application of connectivity models within the review process to enable more detailed analysis of component interfaces. It is also important to develop techniques to identify the knock-on effects of change on other components. In the short to mid-term, the cells of the spreadsheet will be linked to documents and checklists external to the matrix. In order to monitor the progress interface reviews, 'heat maps' are used to distinguish between interfaces where clashes have been resolved from those which are still under review or yet to addressed. In the long term, the connectivity model will be extended so that it can be applied to the bidding phase of projects to assess the consequences of customer requirements as well as used to support procurement decisions including changes in materials or suppliers.

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Using Connectivity Models to Support Design Reviews

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MANAGING COMPLEXITY
BY MODELLING DEPENDENCIES

Overview

- Background
- Bombardier Transportation
- Research approach
- Building the DSM
- Using the DSM for and in Design Reviews
- Outcomes
- Outlook
- Contact data

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Background

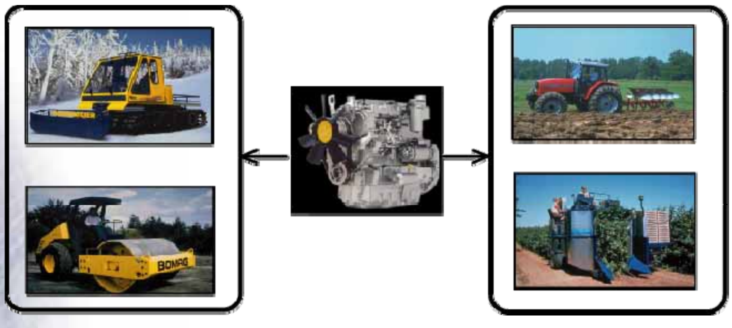
Literature on Design Interface Matrix

- Introduced by Sosa et al. (2003)
  - A technique for analysing component interactions across systems and to understand the effect on design team interactions
  - Based on Pimmler and Eppinger (1994) approach to modelling system interactions within a product
  - 5 types of interactions at system interfaces - spatial, structural, energy, material and information

- Recent applications of Interface Matrices – (None of these are DSMs)
  - Senthilkumar and Varghese (2008)
    - Presented a connectivity model and called it a Design Interface Matrix (DIM)
    - This 'DIM' was used to map of components to disciplines
  - Kusiak (2008)
    - Presented an Interface Structure Matrix (ISM)
    - ISM used to create a mapping between "components to design activities"
    - Identified interfaces are labelled as input, output, or control interfaces

Background

- In this study, DSMs are used to map component interfaces
  - Based on studies component linkages in diesel engines



  - Jarrat et al. (2004) argued that modelling component connectivity with DSMs provided the following benefits:
    - Externalise complex dependency information – Provision of overview
    - Effective information retrieval (with reduced documentation)
    - Useful learning experience
    - Potential to facilitate communication between design teams

Bombardier Overview

Corporate office based in Montréal, Canada	Workforce of 62,900 people worldwide[1]	Revenues of $19.4 bn US[1]	95% of revenues generated outside Canada	Listed on Toronto Stock Exchange (BBD)

[1] for fiscal year ended January 31, 2010

Bombardier Transportation Facts & Figures

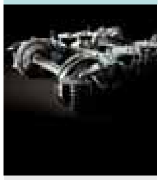
- A global leader in the rail sector
- Broadest product portfolio
- *ECO4* technologies for more sustainable mobility
- Worldwide installed base of more than 100,000 vehicles
- Revenues $ 10 bn US[1]
- Order backlog $ 27.1 bn US[2]
- Global headquarters in Berlin, Germany

ECO4 is a trademark of Bombardier Inc. or its subsidiaries.

[1] for fiscal year ended January 31, 2010; [2] as at January 31, 2010

MANAGING COMPLEXITY
BY MODELLING DEPENDENCIES

Bombardier Transportation – Products and Solutions
The Broadest Portfolio in the Rail Industry

Rail Vehicles	Transportation Systems	Services	Rail Control Solutions	Transit Security Solutions	Propulsion & Controls	Bogies
						
▪ Light rail vehicles ▪ Metros ▪ Commuter trains ▪ Regional trains ▪ Intercity trains ▪ High speed trains ▪ Locomotives	▪ Monorail systems ▪ APM systems ▪ Light rail systems ▪ ART systems ▪ Metro systems ▪ Intercity systems	▪ Fleet management ▪ Operations & maintenance ▪ Material solutions ▪ Vehicle refurbishment ▪ Component reengineering	▪ Integrated control systems ▪ Automatic train protection and operation ▪ Interlocking systems ▪ Wayside equipment ▪ Services	▪ Train-based broadband network ▪ Sensor systems ▪ Security systems recording ▪ Security system viewing and event management	▪ Traction converters ▪ Auxiliary converters ▪ Traction drives ▪ Control and communi-cation	▪ Portfolio to match entire range of rail vehicles ▪ Full scope of service over the lifetime of a bogie

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MANAGING COMPLEXITY
BY MODELLING DEPENDENCIES

Research Approach

- Collaborative study with a rail vehicle manufacturer
- Connectivity model of a rail vehicle was developed by engineers of rail vehicle manufacturer with a researcher providing assistance
- Connectivity model was used to support the internal design review process
- Three users were interviewed after the application of the model
- Further interviews carried out with the process improvement manager and a graduate trainee

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A Study of component Connectivity in Rail Vehicles

Project background

- Rail vehicle to operate on London or South east England rail networks
- Total project time – 1 year
- Time constraint - 50% of “tradition” product development cycle
- Little time for rework; No room for errors during the design process

Approach to Connectivity modelling

- Proxy approach to model building – frequent consultation with research team
- Modelling activities facilitated the graduate trainee engineer
- Primed model evaluated by discipline experts

Building the DSM

- The model was built following guidelines described in (Jarratt et al. 2004)
- A product breakdown of 76 elements was derived for connectivity modelling using the global standard product structure at the rail vehicle manufacturer
- Three forms of component linkages identified:
  - Spatial
  - Geometric
  - Functional
- Type of link was ranked using qualitative indicators of the strength of interactions between component pairs (minor – medium – major)
- 12 engineering specialists provided input for the model by identifying relationships and assessing its strength

A section from completed connectivity matrix

	Dependency Structure Matrix	Carbody Shell	Underframes / Chassis	Sidewalls	Partitions	Roofs	Cab End Segments	Intermediate End Segments	Paint System	Carbody Fittings	Exterior Finishing / Aesthetics	Exterior Finishing - Sanding Gear only	Buffers / Draw Gears	Windows	Gangways	Obstacle Deflectors	Couplers	External Trimming & Skirts	Insulation System	Bogies & Running Gear
	Carbody Shell																			
1	Underframes / Chassis			4	4		2		1			1	4				6	2		
	Spatial																1			
	Geometric			1	1		1		1			1	1				2	1		
	Functional			3	3		1						3				3	1		
2	Sidewalls		4		4	4		1	1					1					1	
3	Partitions		4	4		4														
4	Roofs			4	4		4	4	1									2		
5	Cab End Segments		2			2			1		3		1	1	3	3	4	2		
6	Intermediate End Segments (incl intermediate floor)		4	1		4			1						2		2			
7	Paint System		1	1		1	1	1										1		
	Carbody Fittings																			
8	Exterior Finishing / Aesthetics		1				3							2						
9	Exterior Finishing - Sanding Gear only		1																	
10	Buffers		4				1											2		
11	Windows			1			1				2									
12	Gangways						3	2									3			
13	Obstacle Deflectors						4													
14	Couplers		6												3			1		
15	External Trimming & Skirts		2			2	1		1				2				1			
16	Insulation System			1																
	Bogies & Running Gear																			

- In addition to scores, comments on examples of spatial, geometric and functional links overlaid onto model

Using the DSM for and in Design Reviews

- The connectivity model was presented to two project teams
  - One team agreed to test the DSM, the second team wanted to wait for feedback from the first team
- Design review meetings
  - Attended by senior personnel from different disciplines
  - Approximately 10 members of staff present at each meeting
  - The outcomes can be influenced by promoting effective communication across various technical backgrounds
- Using of the interface connectivity model
  - The interface connectivity model was displayed on a large screen in the meeting room
  - Participants brainstormed to identify potential clashes at component interface
  - By reviewing each interface design engineers discussed in details the challenges to achieving requirements specified for such interfaces

Using the DSM for and in Design Reviews

- The need for an agenda
  - The model supports the Design Review process, including pre-design review and design review meetings and their preparation
    - Design-review preparation: Supports the selection of the engineering specialists, who needs to be participate in the meeting and prepare the agenda
    - Pre-design review: helps to arrange internal small pre-review sessions to carry out the review
    - Design review meeting: the model is used to facilitate discussions and the review steps during the meeting
- The need for an overview
  - no single individual had a complete overview of the different types of interactions between all components
- The need for structure in the review process
  - The review followed along the row of a particular sub-system or component
  - All interfaces were reviewed irrespective of the scores within the connectivity model

Overview

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Study outcomes

- **Verification of earlier studies (Jarrat et al. 2004)**
  - Externalise complex dependency information – Provision of overview
  - Effective information retrieval
  - A memory aid which draws attention to all interfaces concerning components under review

- **New insights from study**
  - Work planning - A vital item to ensuring the appropriate personnel are attending review meetings
  - Work quality - The model could help improve robustness of review processes
  - Unplanned work - The model could help reduce disruptions in the work flow there by saving time as designs are finalised early
    - System engineers were able to concentrate on completing their work schedule without being called upon to address unplanned activities

Study outcomes

- **Summary**
  - The connectivity model of component interfaces enables the engineering team to identify the critical areas concerning system interfaces
  - It helps steers the design review to focus on these key areas
  - It offers a potential reduction in unplanned work due to more rigorous review

  - The true benefit of using connectivity models to support the design process will only be experienced once the first vehicle build is completed.
  - The company is expecting a reduction in non conformity cost and engineering changes associated with system interfaces.

Outlook

Work in progress

- Link of DSM to documents and checklists to support the reporting regarding the interrelationships

Mid to Long term

- DSM model will be applied to following project
  - Support change prediction within the bidding phase and for purchasing
  - Extending the model with an additional information layer (e.g. Safety regulations)