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Issues in Conceptual Design and MBSE Successes: Insights from the Model-Based Conceptual Design Surveys

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Abstract. The INCOSE Model-Based Conceptual Design (MBCD) Working Group was established in 2011 with the purpose of advancing the body of knowledge and practice of systems engineering (SE), through the development and application of model-based systems engineering (MBSE) methodologies to the concept stage of a system's life-cycle. The Working Group strives to achieve its vision through a series of activities conducted by members of the working group. One of these activities was to conduct a survey of people involved in MBCD, with the goal: To identify the issues associated with performing Conceptual Design and areas where MBCD has been successful. As part of this activity, two surveys, one in 2014 and one during 2015, have been conducted. This paper begins with an overview of the first survey and the need for a second survey that arose from the possibility of non-response bias being present in the first survey's results. Following this, the results obtained from the second survey are presented, compared with the results from the first survey and discussed. The key insights the authors uncovered from the results, survey workshops, and symposium presentations on both surveys are also identified. The paper concludes with a discussion on how these results are being used to inform current MBCD WG activities and strategic planning.

Introduction

The INCOSE Model-Based Conceptual Design (MBCD) Working Group (WG) has been established with the vision to "Develop best practice for MBCD". MBCD is defined by the WG as the application of Model-Based Systems Engineering (MBSE) to the concept stage of the generic life-cycle defined by INCOSE in the SE Handbook (Walden, Roedler et al. 2015) and ISO/IEC/IEEE 15288 (ISO/IEC/IEEE 2015), which cites ISO/IEC TR 24748-1:2010(E) (ISO/IEC/IEEE 2011). A good overview of the concept stage can be found in ISO/IEC TR 24748-1:2010(E) (ISO/IEC/IEEE 2011: 25):

> "The Concept Stage begins with initial recognition of a need or a requirement for a new system-of-interest or for the modification to an existing system-of-interest. This is an initial exploration, fact finding, and planning period, when economic, technical, strategic, and market bases are assessed through acquirer/market survey, feasibility analysis and trade-off studies. Acquirer/user feedback to the concept is obtained.
>
> "One or more alternative concepts to meet the identified need or requirement are developed through analysis, feasibility evaluations, estimations (such as cost, schedule, market intelligence and logistics), trade-off studies, and experimental or prototype development and demonstration. The need for one or more enabling systems for development, production, utilization, support and retirement of the system-of-interest is identified and candidate solutions are included in the evaluation of alternatives in order to arrive at a balanced, life cycle solution. Typical outputs are stakeholder requirements, concepts of operation, assessment of feasibility, preliminary system requirements, outline design solutions in the form of drawings, models, prototypes, etc., and concept plans for enabling systems, including whole life cost and human resource requirements estimates and preliminary project schedules."

The importance of conceptual design is highlighted in the INCOSE SE Handbook with: "if the work is done properly in the early stages of the lifecycle, it is possible to avoid recalls and rework in later stages" (Walden, Roedler et al. 2015: 29). MBCD advocates the extensive use of MBSE in the concept stage and seeks to use computer-based models (as opposed to documents) as the primary source of project information (often referred to as 'source of truth'). The computer-based model is employed to support systems engineering processes such as user needs analysis, system specification, architectural design, risk analysis, trade-studies, and verification and validation ((Estefan 2008); (Friedenthal, Moore et al. 2009); (Robinson, Tramoundanis et al. 2010); (Do, Cook et al. 2011); (Cook, Bender et al. 2015)). A profound observation from an MBSE practitioner and notable systems engineer (Logan 2011) is that adoption MBSE effectively mandates that many systems engineering activities are performed and that MBSE inherently promotes good system engineering. Given that, it is widely acknowledged that the application of quality systems engineering saves resources ((Honour 2013); (Elm, Goldenson et al. 2008)). It is not surprising that thoughtful application of MBSE can be expected to contribute to good project outcomes and some prominent returns on investment have been reported. For example, (Richards, Stuart et al. 2009) stated that Westinghouse saved 70% on verification using auto-generated testing for railway switching systems and Saunders (Saunders 2011) stated that Raytheon reduced specification defects by 68% following the introduction of MBSE practices.

As a stepping stone on the path to achieving the vision of the MBCD WG, a WG activity was initiated to build an understanding of the issues and successes people involved in the conceptual design stage have experienced. The activity commenced by emulating the INCOSE SoS WG "pain-points" survey and conducted an initial survey of WG members during 2014. This first survey comprised mostly open-ended questions for respondents to describe their conceptual design issues and MBCD successes. From these responses, issue and success themes were identified and presented (Morris, Harvey et al. 2015). Amongst the data collected from respondents were the geographical regions where they had performed conceptual design. This data highlighted that the majority of respondents had performed conceptual design in the Oceania region, also the centre of gravity of the MBCD WG at the time, which hinted at the possibility of non-response bias being present in the results. In an effort to address concerns that the conceptual design issues and MBCD successes identified from the first survey may not be representative of the entire population of people involved in conceptual design, a second survey was undertaken from 13th July until 28th August 2015.

2014 MBCD Survey

The first MBCD survey was conducted using an online questionnaire from 24th June until 16th July 2014. It comprised a mix of pre-coded, structured questions and open ended free text responses divided into three sections. The first section was used to capture professional background data on the respondent whereas the second section comprised questions to elicit any conceptual design issues that the respondent had encountered. The final section contained questions to elicit any MBCD successes with which the respondent had been involved.

The survey team adopted a grounded theory research methodology, since the goal of the survey was to identify the issues and successes within the conceptual design stage. Grounded theory approaches "begin with the data and use them to develop a theory" (Leedy and Ormrod 2001:140). In this instance, the data was the results collected during the survey. One key approach to analysing data in a grounded theory study is open coding. Open coding is used as a means of "reducing the data to a small set of themes that appear to describe the phenomenon under investigation" (Leedy and Ormrod 2001: 141). This involved the survey team scrutinising, many times, the text supplied by respondents to the questions in the survey.

A total of 39 responses were obtained during the period the survey was open. Qualitative (statistical) and quantitative (open coding) methods were used to analyse the survey responses and the results were presented to a workshop at the 2014 Australian Systems Engineering Workshop (ASEW) for discussion and review. Input from the participants at the workshop led to some changes to the themes of individual issues. Slight changes to the names of the issue themes were discussed and agreed upon. The workshop also provided further insights into the underlying causes of some of the issues and successes. Forty-two conceptual design issues were elicited from the respondents in the 2014 survey, along with 23 MBCD success stories.

A concern regarding the high proportion of respondents who indicated they had worked in conceptual design in the Oceania region, as shown in **Error! Reference source not found.** was raised by both the survey team and workshop attendees at the 2014 ASEW. This raised the possibility of the presence of non-response bias, or a bias in the results due to proportionally lower responses from parts of the overall population (Rea and Parker 2014), in the results of the 2014 survey.

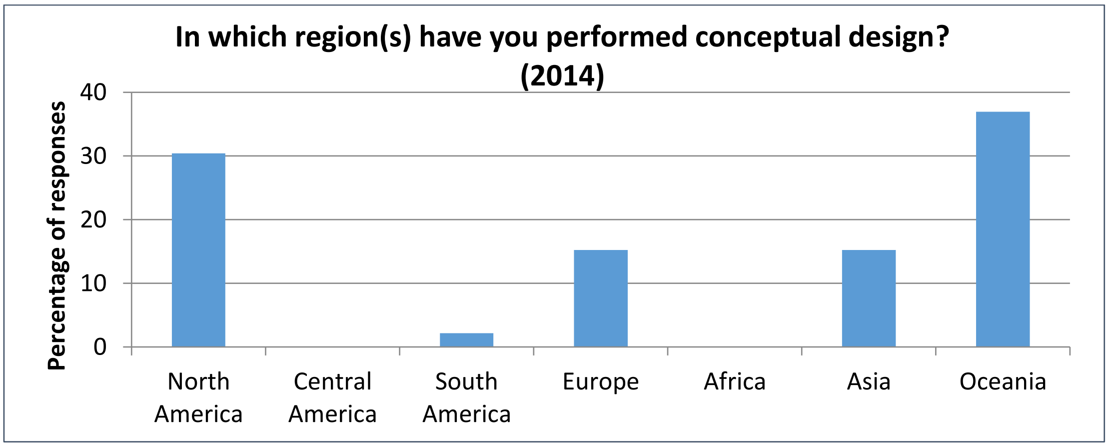


Figure 1: Regions where respondents had performed conceptual design from the 2014 MBCD survey.

The themes that were open coded by the survey team, then reviewed and updated by participants at the 2014 ASEW, from the responses to the open-ended question “Please give a description of the issue and the context in which it occurred (e.g. project/program data, those involved in the issue, impact of the issue, etc.)” are shown in Figure 2.

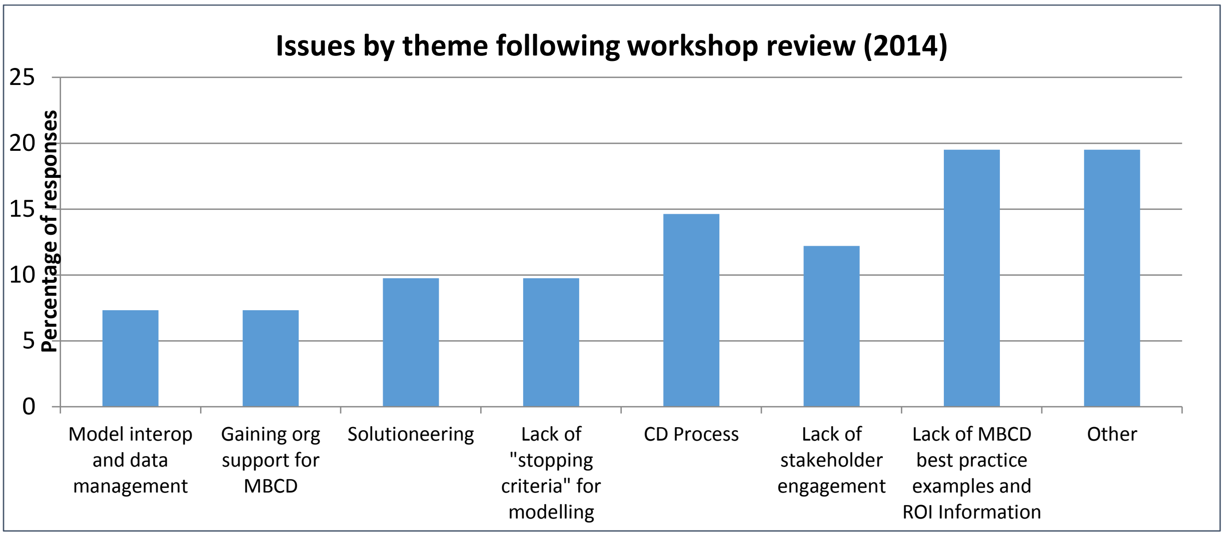


Figure 2: Histogram of issue themes from the 2014 MBCD survey.

It can be seen from Figure 2 the “lack of best practice examples and ROI information” theme, along with the “other” theme, were the most common themes of the issues provided by respondents. Issues that fell into the “other” theme comprised issues mostly more broadly related to systems engineering, along with issues where the descriptions were difficult to open code. During the workshop to review the themes coded from the responses by the authors, several insights about the issues were gained including the need for the project SE team to “provide the right information to engage the stakeholders” during conceptual design.

Interestingly, in nearly 40% of the conceptual design issues that were elicited where MBSE was used, respondents indicated that using MBSE exacerbated the issue. Respondents were asked the question “If MBSE was used, could you briefly explain how it made your issue better or worse?”. Analysis of the themes where MBSE exacerbated the issue reveals that most often, these issues were in the “lack of stopping criteria for modelling” and the “lack of best practice and ROI information” themes as shown in Figure 3.

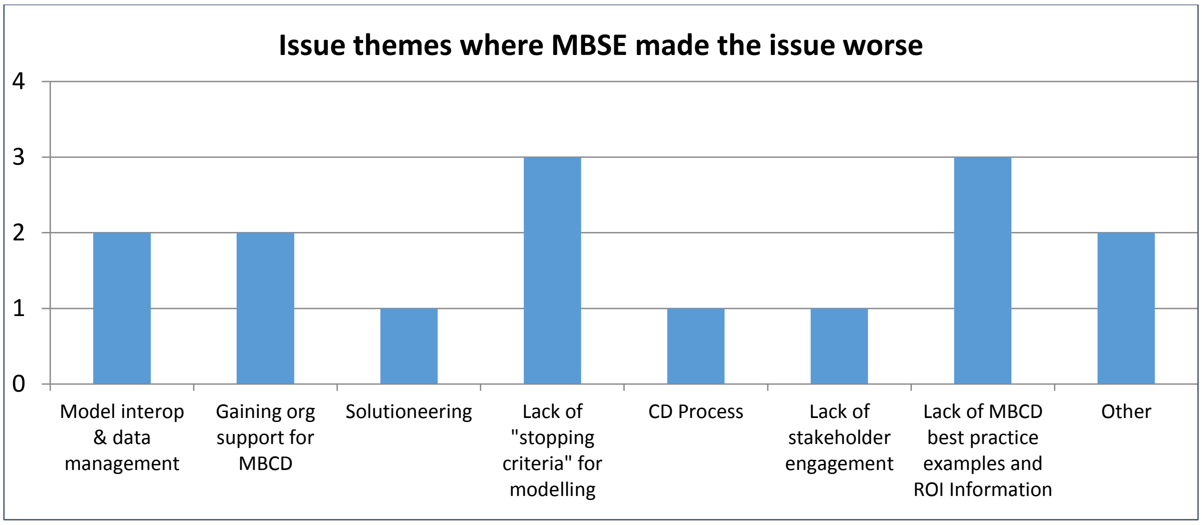


Figure 3: Histogram of issue themes following workshop review, where the respondent indicated MBSE exacerbated the issue.

Figure 4 shows the MBCD success themes identified by asking the respondent to "describe up to three MBCD successes (e.g. project/program etc.) and elaborate on why you believe it was a success." Again, the qualitative technique of open coding was used by the survey team to identify the success themes from the text provided in response to the MBCD success question.

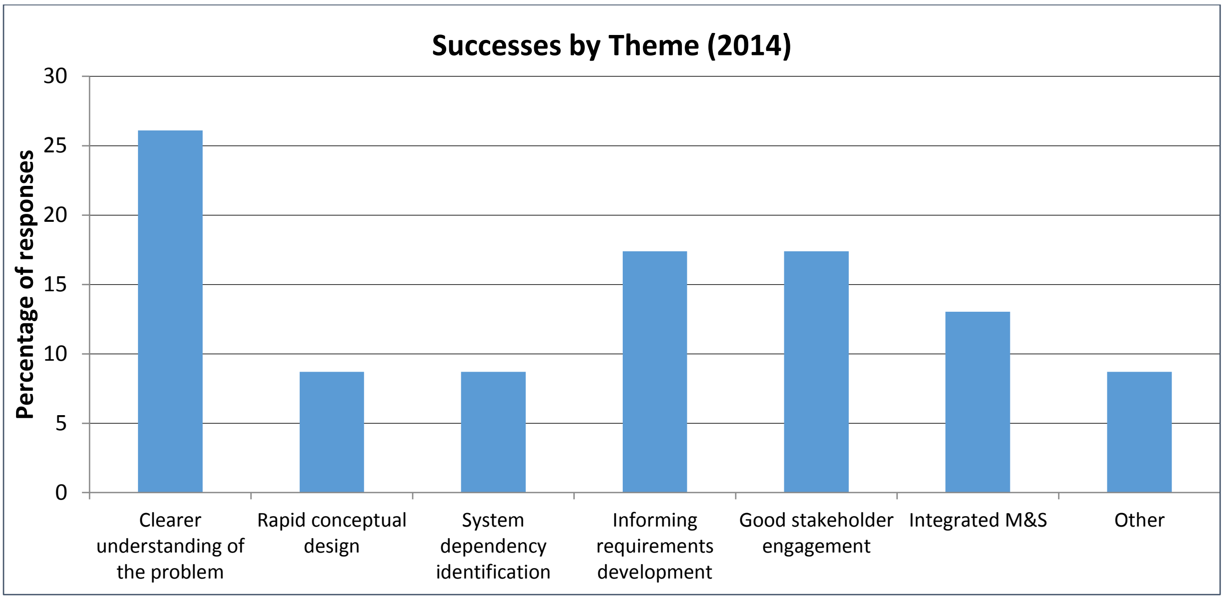


Figure 4: Histogram of the MBCD success themes from the 2014 MBCD survey.

It can be seen from Figure 4 the most common MBCD success theme is the "clearer understanding of the problem" theme, followed by the "informing requirements development" and "good stakeholder engagement" themes. As for the issues themes, there are conceivably many links between the themes. For example the "informing requirements development" and "clearer understanding of the problem" themes appear to be related and can conceivably be linked to "good stakeholder engagement" in that "good stakeholder engagement" is required to inform requirements and develop a clear definition of the problem.

2015 MBCD Survey

The concerns surrounding the possibility of non-response bias being present in the results of the first survey, led to the MBCD WG survey team performing a second survey in 2015. The second survey used the structure of the first, which comprised three sections, but utilised more closed-ended questions to minimise the time required to complete the questionnaire to reduce the impost on participants. The first section collected professional data on the respondent. The second section captured data on the conceptual design issues the respondent had encountered and the final section collected data on MBCD successes the respondent had experienced. In the conceptual design issue and MBCD successes sections, respondents were asked to reflect on their experience and select the frequency with which they had encountered a set of issues and success themes. The themes were contained in statements constructed from the results of the first MBCD survey (e.g. “I have experienced stakeholders ‘solutioneering’”). Respondents also had the opportunity to provide a free text response for any other issues and successes they had experienced if they felt the categories were not appropriate or did not reflect their experience.

Forty responses were collected during the period that the second survey was open. As with the first survey, the highest proportion of responses (37.5%) came from people who had performed conceptual design in the Oceania region. However, this time, responses were more evenly spread across the North American (33.3%) and European (23%) regions as shown in Figure 5.

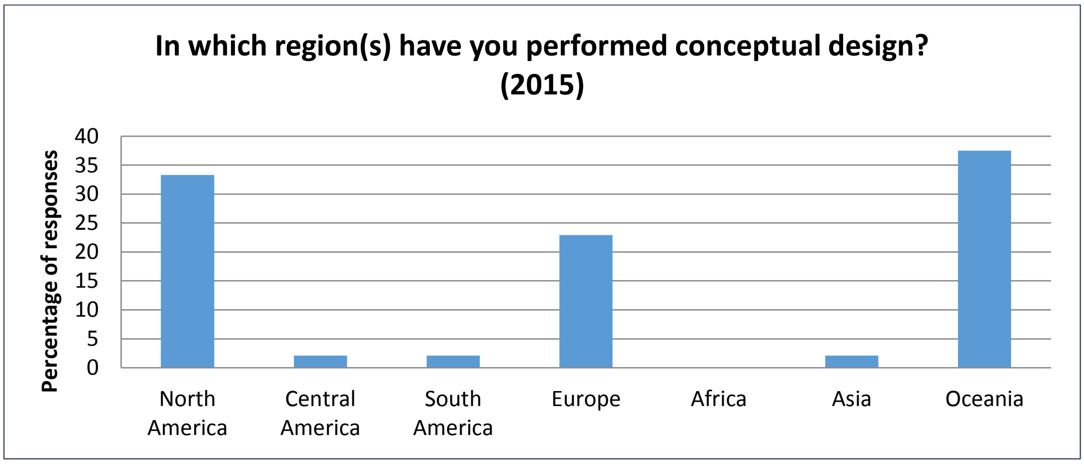


Figure 5: Regions where respondents had performed conceptual design from the 2015 MBCD survey.

The issue section in the 2015 survey asked respondents to select the frequency with which they had experienced each of the issue themes identified from the 2014 survey. Respondents were able to make comments against each issue theme and also provide other conceptual design issues they had experienced. The conceptual design issue themes respondents indicated they had experienced most often were stakeholder “solutioneering” (i.e. specifying a solution without first exploring and understanding the problem) and a lack of stakeholder engagement, as shown in Figure 6.

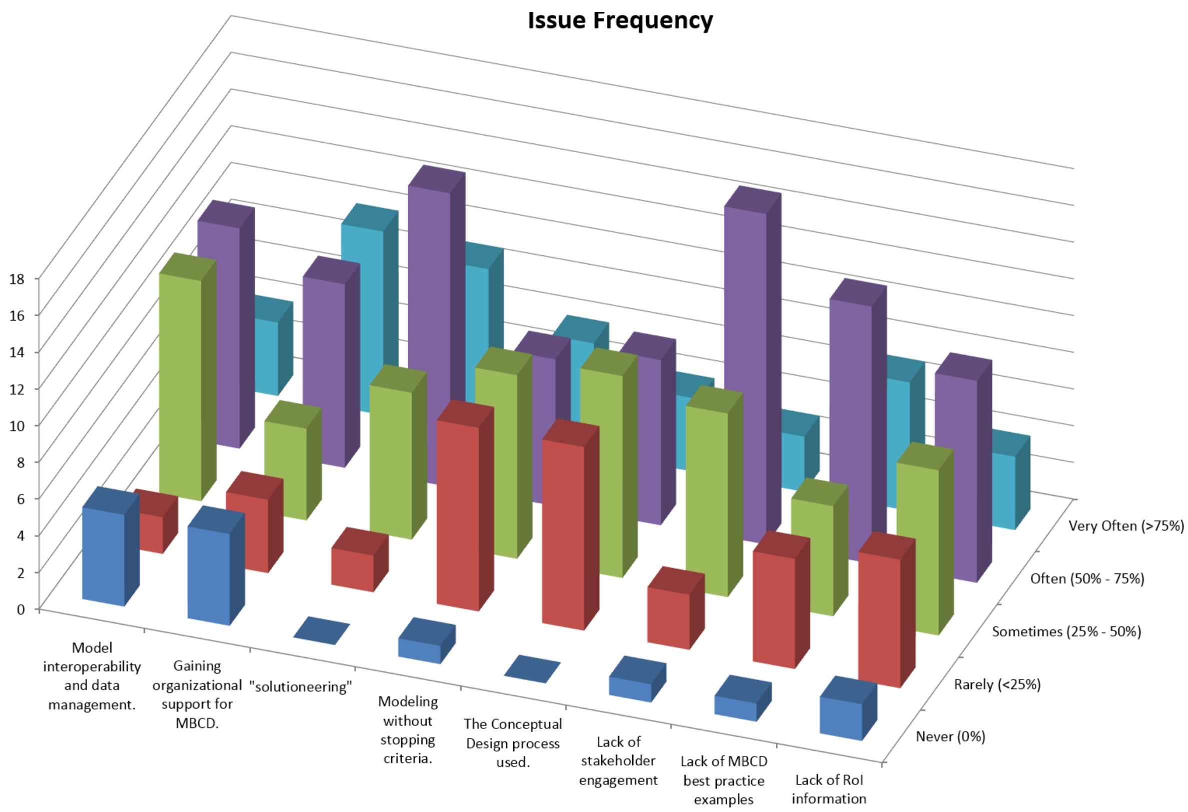


Figure 6: Three dimensional histogram of the number of responses for each issue theme and the frequency that respondents had experienced them.

The MBCD success themes respondents chose most often were that MBCD had "provided clearer understanding of the problem space", "helped inform requirements development" and "identifying system dependencies".

Respondents were also able to suggest and describe other conceptual design issues and MBCD successes in text boxes provided in the 2015 survey. When these free-text responses were open-coded, most fit into the existing themes, although several new themes were identified. For the conceptual design issues, the new themes included:

- **Requirements uncertainty** – i.e. changes in requirements as the conceptual design progresses.
- **Lack of a common taxonomy** – "impreciseness of language".

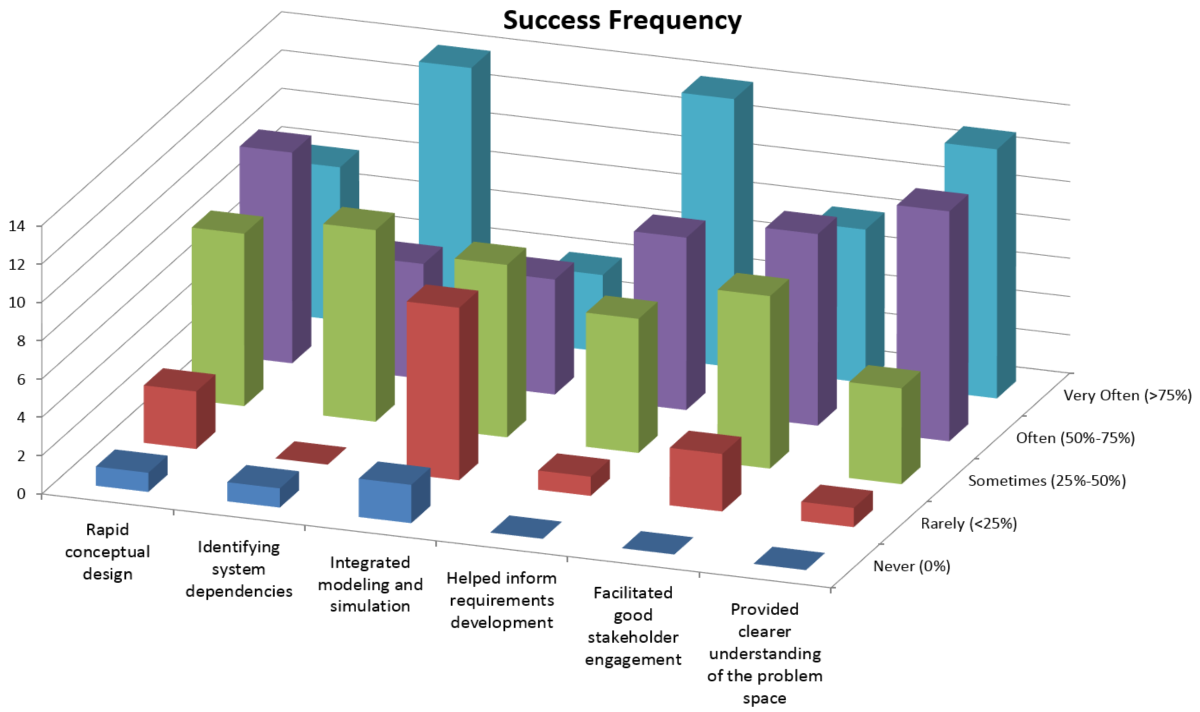


Figure 7: Three dimensional histogram of the number of responses for each success theme and the frequency that respondents had experienced them.

For the MBCD successes, the new themes included:

- **Facilitated creative thought** – i.e. MBCD helps the systems engineer focus on developing a concept rather than writing a specification.
- **Facilitated "reverse SE"** – Supports exploring the understanding of aspects of the problem space in whatever order is considered appropriate e.g. model the functions first, then reverse engineer the requirements.

Comparison of Results from the 2014 and 2015 Surveys

Figure 4 and Figure 5, showed that the regions where respondents had performed conceptual design were similar for the 2014 and 2015 surveys. The industries in which respondents had performed conceptual design were very similar as shown in Figure 8 and Figure 9.

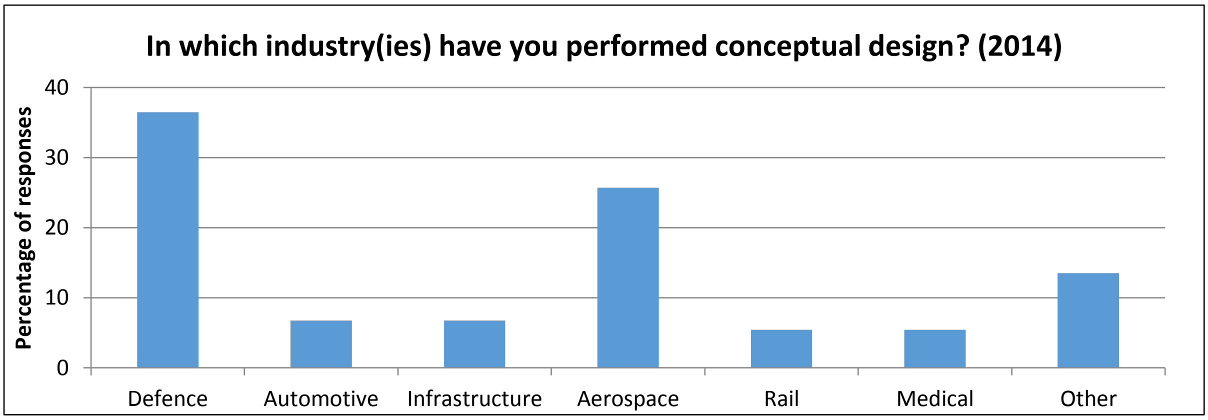


Figure 8: Industries in which respondents had performed conceptual design in 2014.

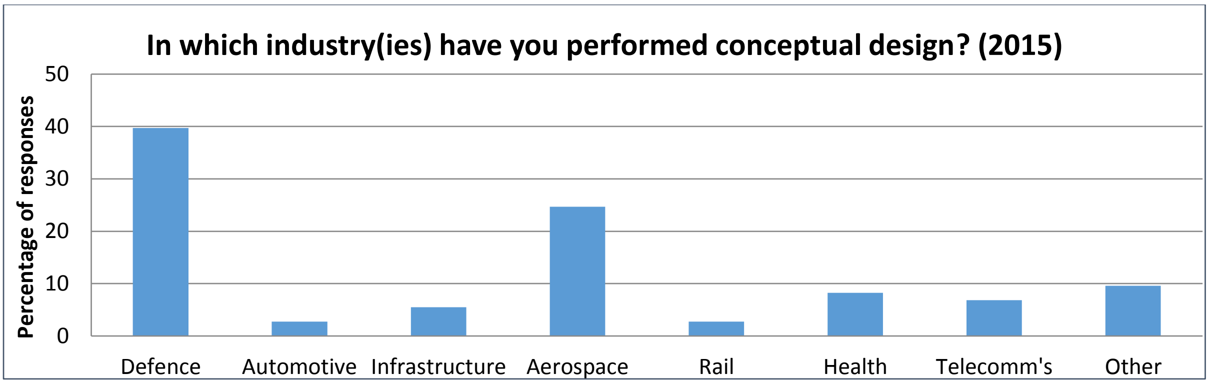
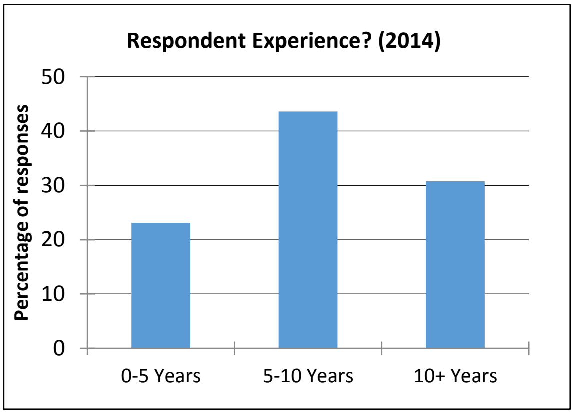
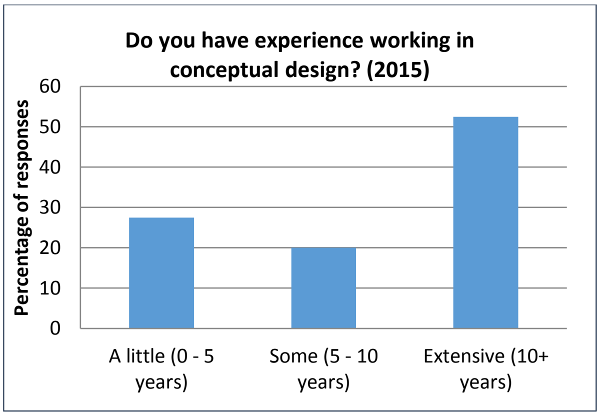


Figure 9: Industries in which respondents had perform9ed conceptual design in 2015.

There were differences between the experience (in terms of years working in conceptual design) of respondents, with the highest proportion of respondents indicating they had between five and 10 years' experience in 2014 and more than 10 years' experience in 2015 as shown in Figure 10.



(a)



(b)

Figure 10: Comparison of respondent's experience working in conceptual design in (a) 2014 and (b) 2015.

Due to the use of structured questions in the 2015 survey for the conceptual design issues and MBCD successes sections of the survey, it is difficult to make a like-for-like comparison with the 2014 survey results. Nonetheless, weighted averages of each of the issue and success themes were calculated to give an indication of the leading issue and success themes in the 2015 survey. A comparison of the weighted averages for the issue themes in 2015 against the histogram of issue themes from 2014 is given in Figure 11.

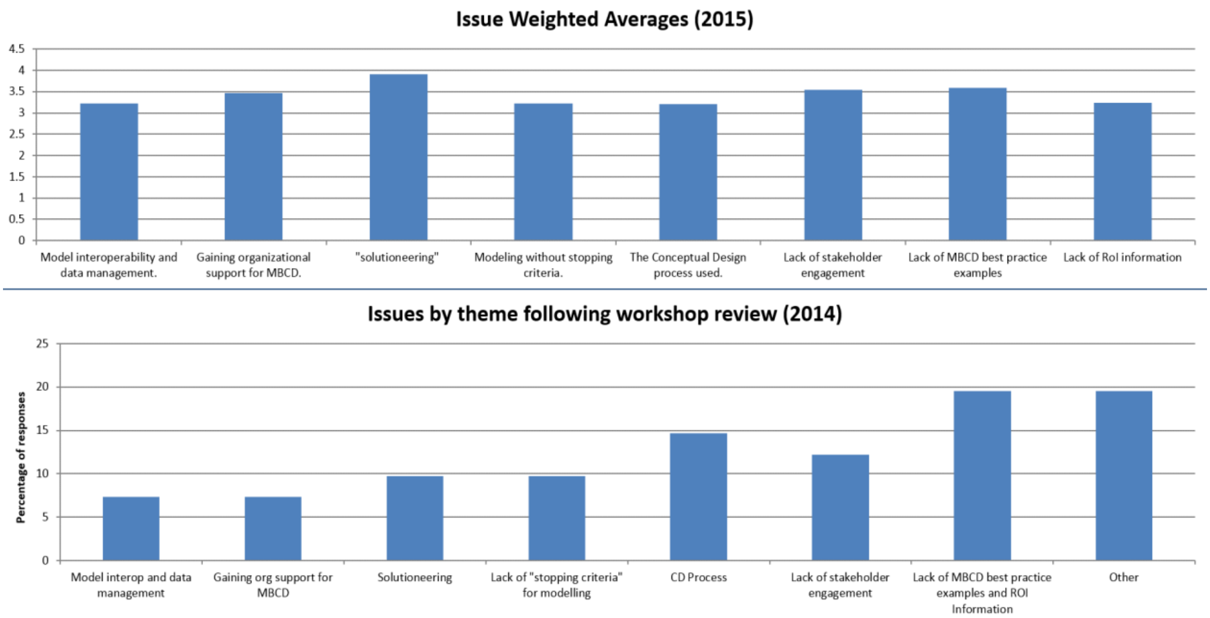


Figure 11: Comparison of the issue themes weighted averages in 2015 (top) and percentage of responses in 2014 (bottom).

From Figure 11 it can be seen that in 2015 the "solutioneering" theme had the highest weighted average, whilst it did not rank so highly in the 2014 survey. It is also worth noting from Figure 11 that in 2014 the "lack of MBCD best practice examples and ROI information" issue was the highest ranking issue in 2014. In the 2015 survey, this theme was split into the "lack of MBCD best practice examples" and "lack of ROI information" themes. If the weighted averages of these two themes are combined, then this issue would rank highest in 2015 as well.

Using the approach of calculating the weighted averages of the MBCD success themes from the 2015 survey results, a comparison can be made with the results from the 2014 survey, as shown in Figure 12.

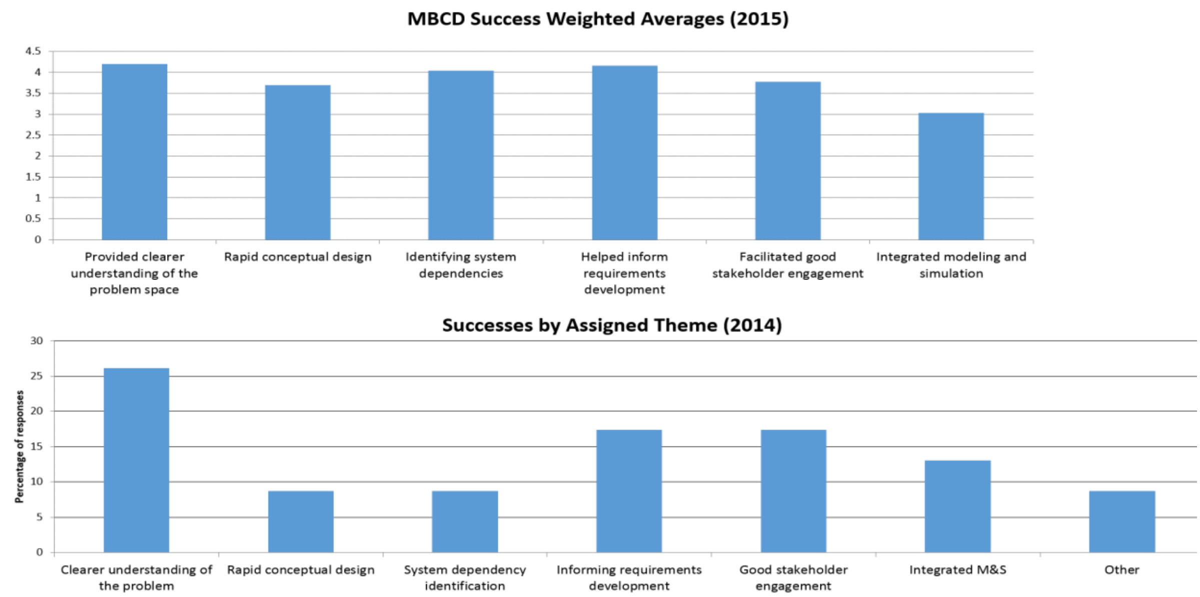


Figure 12: Comparison of the MBCD success themes weighted averages in 2015 (top) and percentage of responses in 2014 (bottom).

Comparing the top and bottom graphs in Figure 12, it can be seen that the rankings of the top two MBCD success themes, “clearer understanding of the problem space” and that MBCD “helped inform requirements development” are the same. However, the “identifying system dependencies” theme ranks several successes higher in the 2015 results compared to the 2014 results.

Key Insights and Discussion

The two MBCD surveys have uncovered several insights into the field of conceptual design and many discussion points. Following a presentation of the results from the 2015 MBCD survey at the 2015 ASEW held in Sydney, Australia, a panel session was held to discuss possible means of addressing some of the key issues identified by respondents. The “lack of stakeholder engagement” issue was the subject of a lengthy discussion and similar to the point raised during the 2014 ASEW MBCD survey workshop, the topic was linked to providing stakeholders with useful, interesting information as a means of engaging the stakeholders and convincing them of the efficacy of the approach. Panel session participants indicated this could be facilitated through more engaging graphics in MBSE tools, easier access of MBSE data through other presentation tools and the employment of “soft” skills from the MBCD team.

Another key insight from the surveys is that the conceptual design process issue is linked to other issues and also broader than MBCD. Respondent’s highlighted the need to be creative, flexible and non-solution specific during conceptual design in both surveys, with one stating: “there are process issues with or without MBCD”. This needs to be considered in any future activities the MBCD WG, particularly the planned activity of developing a best practice guide. The guide should cover not only model-based approaches to conceptual design, but how to perform good conceptual design in a model-based way. In other words, the best practice guide needs to outline an MBCD methodology. Any MBCD methodology should include methods, tools and techniques for facilitating successful conceptual design. In particular the methodology needs to ensure good stakeholder engagement, minimise solutioneering, and support users and stakeholder through the process.

Identified in the INCOSE SE Handbook (Walden, Roedler et al. 2015), key outcomes of a successful concept stage is the clear derivation of the problem definition and the resultant systems requirement. From both the surveys, it was identified that a “clearer understanding of the problem” and “informing requirements development” were key success themes for MBCD. From this result it can be concluded that MBCD has great potential to enhance the outcomes of the concept stage. In addition, both the derivation of the problem definition and the resultant systems requirement are highly reliant on good engagement from a broad and diverse range of stakeholder. Both surveys found that MBCD improved “good stakeholder engagement”, thereby further improving the potential to enhance the outcomes of the concept stage.

Another key insight worth noting is that any modelling performed during MBCD needs to have a purpose. This insight comes from the 2014 survey where respondents indicated that in nearly 40% of their conceptual design issues, MBSE exacerbated the issue. The issues most exacerbated through the use of MBSE were “lack of stopping criteria for modelling” and “lack of best practice examples and ROI information”. The MBCD WG could look to provide practitioners with information on the level of modelling performed in successful MBCD within a set of case studies and best practice guide.

Finally, the concerns regarding non-response bias being present in the results of the first survey have been somewhat addressed by the results of the second survey. The similar results, where again (as shown in Figure 5), the most common region where respondents had performed conceptual design was the Oceania region, imply a trend rather than a discrepancy. This trend may be linked to the MBCD WG originating in Australia and initially comprising a membership dominated by people working there. Both surveys however, were advertised more broadly that the WG membership. The MBCD WG is looking to foster closer ties to the MBCD community in the northern hemisphere through the growth of a "satellite" team in the United States led by two United States based WG co-chairs. This team is already playing an active role in INCOSE events in the United States and gathering traction with local practitioners.

Conclusions

The MBCD WG survey activity has provided useful data on the types of issues people have experienced while working in conceptual design, along with the successes people have experienced through the application of MBSE to conceptual design. The MBCD WG continues to incorporate these issues and successes into the WG strategy and planning of ongoing and future activities. The major activity currently being undertaken by the WG is the collection of a set of MBCD case studies that will help address the leading issue in both surveys: "lack of best practice examples" and "lack of ROI information". These case studies will also be a useful reference for MBCD practitioners as they could provide insights into addressing other issues including the "lack of stakeholder engagement" and "the conceptual design process". A subsequent WG activity is planned to distil the case studies into a code of best practice.

Acknowledgements

The authors would like to acknowledge the input and advice provided by the INCOSE MBCD WG and particularly the WG steering committee. The authors are also grateful for the input and suggestions provided by those who attended the survey workshop and presentations at the 2014 and 2015 ASEWs. Most importantly, the authors would like to thank the people who gave their valuable time to complete the surveys.

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Biographies

Brett Morris is a Naval Architect/Systems Engineer who joined the Defence Science and Technology Group in 2007. He has previously worked for the RAN in the Directorate of Navy Platform Systems and has conducted research in the fields of Naval ship concept design, modelling and simulation of ship performance, along with MBSE. Brett has a Grad. Dip. in Systems Engineering, a BE (Nav. Arch.) and is currently undertaking part-time research towards a PhD.

Dr David Harvey is a systems engineer with a particular interest in Model-Based Systems Engineering (MBSE). He holds a bachelor degree and a doctorate both in the field of mechatronics. He is currently the Chief Systems Engineer at Shoal Group Pty Ltd (formerly Aerospace Concepts). Shoal has developed an MBSE approach and tailored tool to assist in complex system definition in conjunction with Australian Defence partners. As well as leading this development, he is also involved in applying the tool and approach to capability definition in major Australian Defence projects. David is also the chair of INCOSE's Model-Based Conceptual Design Working Group.

Kevin Robinson has been working in the field of Defence Science since 1992. After graduating from Cranfield University (UK) with an MSc in Electronic Systems Design (Control Systems), he joined what became the UK's Defence Science and Technology Laboratory (Dstl) where he initially evaluated air-launched guided weapons, predominately the Advanced Short Range Air to Air Missile (ASRAAM), before becoming the technical lead and manager on a number of guided weapon support programmes. In 2000 he qualified as a Chartered Engineer with the Royal Aeronautical Society and in 2004 completed an MSc in Advanced Systems Engineering (Guided Weapons) with Loughborough

University (UK). In 2005 he left Dstl and joined the Australian Defence Science and Technology Organisation (DSTO). At DSTO he became the Project Science and Technology Advisor (PSTA) for the Follow on Stand-Off Weapon (FOSOW) acquisition programme and undertook research on model-based systems engineering (MBSE).

In 2011 he became the Head of Weapons Capability Analysis in Weapons Systems Division, before moving to the role of Group Leader of the Systems Integration and Tactical Networking Science and Technology Capability in Land Division.

Kevin has also been the Chair of INCOSE's Model-based Conceptual Design Working Group.

Stephen Cook is an adjunct professor at the University of Adelaide where he works in the Entrepreneurship, Commercialisation and Innovation Centre undertaking research in system of systems engineering and complex project management theory and practice. Until June 2014 he was the Professor of Systems Engineering at the University of South Australia where he led a number of research concentrations in the field. Preceding this he accumulated twenty years of industrial R&D and SE experience spanning aerospace and defence communications systems in both DSTO and industry. His research interests focus on the development of MBSE practices, the SE of large-scale defence capabilities, and relating complexity theory to SE practice and organisational improvement. He also works with Shoal Engineering Pty Ltd applying his knowledge to a range of systems engineering management and research challenges. Prof Cook is a past President of the Systems Engineering Society of Australia, an INCOSE Fellow, a Fellow of Engineers Australia, a Fellow of the Institution of Engineering and Technology (UK), and a Member of the Omega Alpha Association.