DESIGNING IN A UNIVERSITY AND START-UP CONTEXT: AN ANALYSIS ON ENGINEERING CHANGE PROPAGATION

E. C. Y. Koh, R. A. Duran-Novoa, J. D. Weigl and M. Henz

Keywords: entrepreneurship, start-ups, engineering change, change propagation

1. Introduction

Engineering Change (EC) is an important phenomenon in the design of products and systems, accounting for nearly one third of work effort [Langer et al. 2012]. Its significance is recognised by the scientific community, which has developed modelling tools to support its prediction and management [de Weck et al. 2012]. However, most of the work seeks to address engineering change in mature firms [Koh et al. 2013], [Fernandes et al. 2015], [Tang and Yin 2016]. Few studies have documented the impact of engineering change in a start-up context and in university design projects [Weigl and Koh 2014]. Given that mature firms and start-ups operate differently as pointed out by Hölttä-Otto et al. [2013] and De Lessio et al. [2015], there is a need to better understand how EC and its propagation occur beyond a mature firm setup. For instance, mature firms who redesign their own products will have direct access to information pertinent to their previous designs while start-ups who redesign products produced by others will have to make assumptions about the original design. Without an established supply chain and reputation, start-ups who seek to design new products may struggle to get support from suppliers as well. These challenges are also common in university design projects. Indeed, many universities are increasingly striving to develop engineering design programmes that reflect the characteristics of early start-ups [Loh 2015]. This work therefore seeks to address the gap in the literature by examining the propagation of engineering change when designing in a university and start-up context. More specifically, it uses a case-study approach [Teegavarapu et al. 2008], [Yin 2013] to analyse the evolution of change dependencies during an electrical motorcycle redesign project undertaken by a university start-up team.

2. Modelling engineering change

Engineering Change is usually referred to as "any alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time" [Jarratt et al. 2011]. In addition, the propagation of EC, or Engineering Change Propagation (ECP), is usually referred to as "any process by which an engineering change to parts of a product results in one or more additional engineering changes to other parts of the product, when those changes would not otherwise have been required" [Koh et al. 2012]. There are various ways to model EC and its propagation. However, as a compilation of previous change modelling work was recently put together by Jarratt et al. [2011], an extensive literature review is not reproduced in this paper. Instead, focus is placed on the modelling requirement, which is to capture how engineering change occur and propagate. One method that fulfills

this requirement is Koh et al. [2015]. The method seeks to prioritise modularisation efforts and uses a Domain Mapping Matrix (DMM) to map the dependencies between change requirements and product components and a Design Structure Matrix (DSM) to model change propagation between product components (see [Eppinger and Browning 2012] on DSM and DMM). This is illustrated in Figure 1 and 2 where change requirements derived from customers and within the organisation are mapped to the product components directly affected (see Figure 1), and subsequently to other product components indirectly affected (see Figure 2). For instance, Requirement A in Figure 1 affects Component 1 and changing Component 1 can subsequently affect Component 4 as shown in Figure 2. Depending on the application, the dependencies modelled can be based on change forecasts to support change prediction or previous change occurrences to support post-mortem change analysis.

DMM	Requirement A	Requirement B
Component 1	X	
Component 2	X	X
Component 3		X
Component 4		X

Figure 1. Mapping change requirements to product components in a DMM

Initiating

DSM	Component 1	Component 2	Component 3	Component 4
Component 1	■		X	
Component 2		■		X
Component 3			■	X
Component 4	X			■

Affected

Figure 2. Mapping interdependencies between components in a DSM

Given that the DMM and DSM described above have the necessary basic structure to capture and examine the evolution of change dependencies from change requirements to product components, they are used in this work as a means to record actual change occurrences that took place over the course of the case study period. Further details on how the DMM and DSM were used in this work is presented in Section 4.

3. Methodology

This research uses a case-study approach [Teegavarapu et al. 2008], [Yin 2013] to analyse the evolution of change dependencies when designing in a university/startup context. In this paper, we describe the first two phases of the work done - "Define & Design" and "Prepare, Collect & Analyse" (see Figure 3). As presented in the introduction, we hypothesise that the occurrence and propagation of EC in university/start-up design projects differ from those observed in mature firms. A university design

project with a start-up mission was thus selected as a case to be studied. Change data was elicited regularly from the project supervisors and was captured using a DMM and a DSM. This paper presents the data captured and the initial findings.
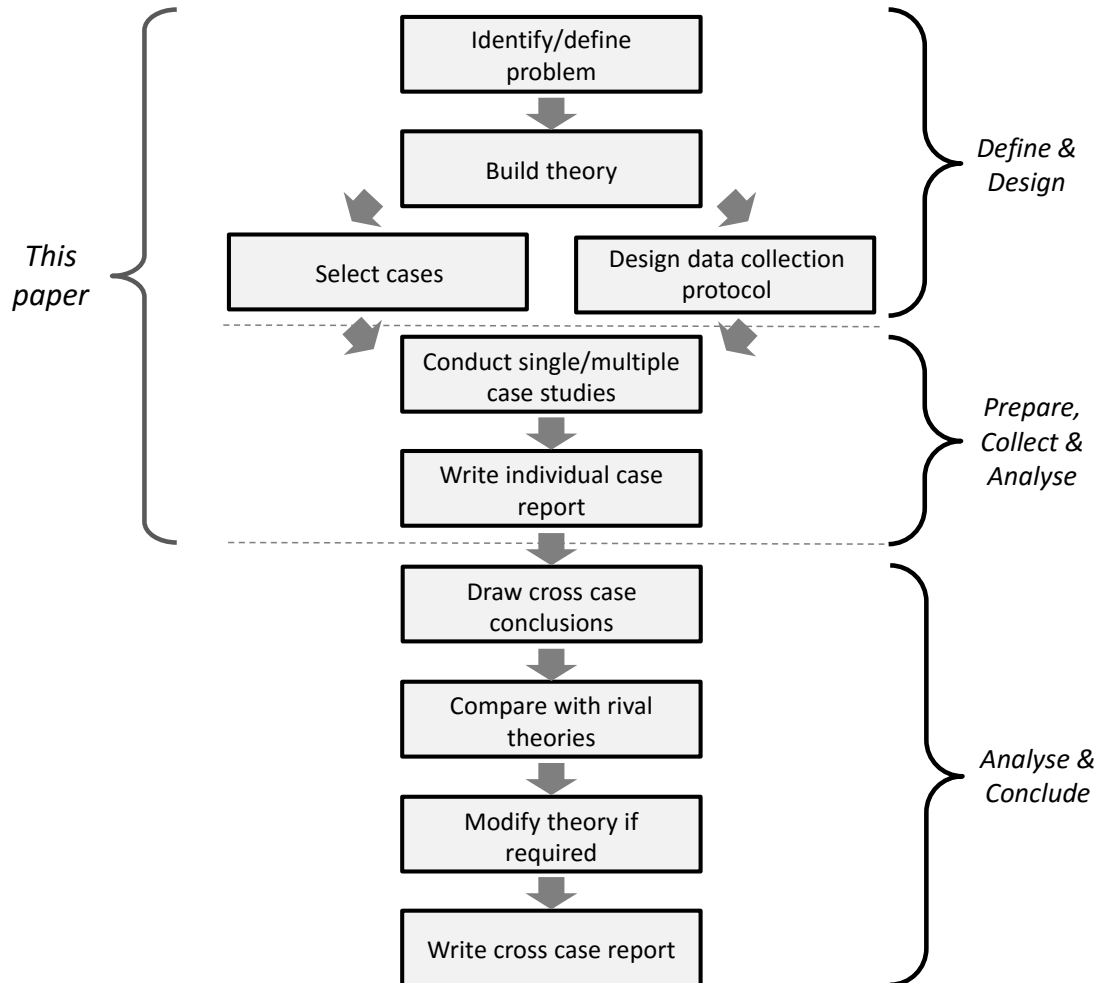

Figure 3. Case study method (adapted from [Teegavarapu et al. 2008])

4. Case study: Electrical motorcycle modification project

The case example studied in this work is a design project that involves the modification of a standard combustion motorcycle towards electrical drive. The modified motorcycle (referred to as 'E-Bike') required conceptual and practical design work, and concluded its first stage of development with the participation of the World Advanced Vehicle Expedition in 2014 (Team Frogworks, http://www.wavetrophy.com/en/history/wave-2014/teams/). Figure 4 shows a picture of the E-Bike. Despite starting off as a university project at the Design-Centric Programme (Faculty of Engineering, National University of Singapore), the E-Bike design team functioned as a start-up as described in [Hölttä-Otto et al. 2013], [Song et al. 2014]. The design team comprising of 2 project supervisors and 7 undergraduate students. The 2 project supervisors have complete autonomy in deciding the direction and management of the team (To ensure data integrity, the researchers of this study did not participate in any of the design activities). Overall, the E-Bike team aims to commercialise the design and operated with tight deadlines, limited budget and resources, low bureaucratic inertia, and low restriction on suppliers. The project therefore offered a suitable context to examine the occurrence and propagation of engineering change when designing in a university/start-up environment.

Figure 4. The converted 'E-Bike'

4.1 Data collection

The collection of data began in September 2013 and ended in January 2015. The data collected include the change requirements formulated and the components changed, together with the associated dates and observed dependencies. The data was captured from the project supervisors of E-Bike (third and fourth author of this paper) by the researchers of this study (first and second author of this paper) using DMM and DSM conventions in Microsoft Excel. Due to resource limitation, the impact of change such as the additional workload incurred by the team was not captured in this work. The list of change requirements captured is as follows:

- Req. A: Provide a 'professional' engineering look with the electrical drive installed
- Req. B: Add a Data Acquisition System
- Req. C: Increase range and reliability
- Req. D: Increase driving performance
- Req. E: Replace damaged parts when required

Next, the E-Bike was decomposed into components. According to the project supervisors, the decomposition of the E-Bike was guided by the commercial availability of the parts. For example, an electrical converter is considered as one component in this project despite having multiple parts as the entire converter can be obtained commercially. On the other hand, although several support bars used in this project could be seen as a single 'support frame' by an external observer, they were considered as separate components as they needed to be designed, manufactured, and assembled separately. By following this logic, 55 components were identified in total by the project supervisors. The change requirements were subsequently mapped to the components targeted for change in a DMM (see Figure 5). The mapping was carried out by both the project supervisors and the researchers, and it was updated 15 times over the course of the project to capture the evolution of change dependencies between change requirements and components. For instance, Figure 5 shows an excerpt of the requirement-component mapping captured on the 24th of September, 2014 (1 year into the project). A description of the entry codes used in the DMM is provided in Table 1.

Table 1. Entry codes for change statuses

Change Status		Entry code
Planned :	Changes declared on a component at the beginning of the design project	P
Unplanned :	Changes declared on a component during the design project	U
Rechanged :	Changes declared on a previously completed planned or unplanned change	R
Cancelled :	Terminated changes	C
Unchanged :	No changes made (yet)	Unshaded cell
In progress :	Ongoing changes	Light grey cell
Finished :	Completed changes	Dark grey cell

DESIGN ORGANISATION AND MANAGEMENT

DMM (Req. to Comp.) 24 September 2014		Req. A	Req. B	Req. C	Req. D	Req. E
12V DC-DC converter	Comp. 1	P		U	U	
12V Fuse	Comp. 2				U	
12V Fuse holder	Comp. 3				U	
12V system main switch	Comp. 4	P			U	
Battery lower set	Comp. 5			P	U	
Battery upper set	Comp. 6			P	U	
Battery box lower	Comp. 7	P			R	U
Battery box upper	Comp. 8	P			R	U
...						
Sprocket	Comp. 19	U			C	
...						
Motor bike rack	Comp. 55			U		

Figure 5. An excerpt of the requirement-component dependencies observed

With reference to Table 1 and Figure 5, it can be seen that the '12V system main switch' (Comp. 4) needed to be changed to address the requirement 'Provide a 'professional' engineering look with the electrical drive installed' (Req. A). The change was planned at the beginning of the project and it was completed (Entry code = P, Dark grey cell). An unplanned change was declared on '12V DC-DC converter' (Comp. 1) to address the requirement 'Increase driving performance' (Req. D) during the project and the change was ongoing at the time of data entry (Entry code = U, Light grey cell). The 'Battery box upper' (Comp. 8) was rechanged to address Req. D as well, and the change was completed prior to the time of data entry (Entry code = R, Dark grey cell). The 'Sprocket' (Comp. 19) was also initially targeted for change due to Req. D, but it was later cancelled before any change was made (Entry code = C, Unshaded cell).

Figure 6 shows an excerpt of the component-component change dependencies also captured on the 24th of September, 2014. The mapping was carried out by both the project supervisors and the researchers. It can be seen that on the date of entry, changes made on the '12V DC-DC converter' (Comp. 1) had propagated to the '12V Fuse' (Comp. 2) and the '12V Fuse holder' (Comp. 3). Changes made on the 'Battery lower set' (Comp. 5) had also propagated to the 'Battery upper set' (Comp. 6). The value '1' entered in the respective cells indicates that change propagation between the said components had only happened once by the date of entry. In total, there were 30 cases of change propagation documented on the 24th of September, 2014.

DSM (Comp. to Comp.) 24 September 2014		Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7	Comp. 8	...	Comp. 55
12V DC-DC converter	Comp. 1	■									
12V Fuse	Comp. 2	1	■								
12V Fuse holder	Comp. 3	1		■							
12V system main switch	Comp. 4				■						
Battery lower set	Comp. 5					■		1			
Battery upper set	Comp. 6					1	■				
Battery box lower	Comp. 7							■			
Battery box upper	Comp. 8							1	■		
⋮											
Motor bike rack	Comp. 55										■

Figure 6. An excerpt of the component-component dependencies observed

4.2 Results

Based on the data collected, there were 152 changes recorded. 50 of the changes were planned at the beginning of the project while the other 102 changes emerged later during the project. Out of the 102 changes that emerged later, 55 changes were unplanned, 16 changes were for rechanging previously completed changes (11 were previously planned changes and 5 were previously unplanned changes), and 31 changes were due to change propagation between components. 8 out of the total 152 changes were cancelled during the project. 6 of the cancelled changes were planned changes while the other 2 were unplanned changes. Table 2 shows the percentage breakdown between the change categories.

Table 2. Percentage breakdown between change categories

	Total Changes	Planned Changes	Unplanned Changes	Rechanged Changes	Change Propagation	Cancelled Changes
Number	152	50	55	16	31	8
Percentage	100%	33%	36%	11%	20%	5%

With reference to Table 2, it can be seen that only 33% of all changes were planned. Unplanned changes and rechanges account for 47% (36% + 11%). Change propagation was also significant, accounting for 20% of all changes made. Figure 7 shows the number of new requirement-component dependencies alongside with the number of new component-component dependencies across different time intervals. It can be seen that the number of new component-component dependencies (i.e. change propagation) did not increase with the number of new requirement-component dependencies. In fact, with reference to Table 3, the Pearson's correlation coefficient between the two sets of data was found to be -0.211 (no correlation).
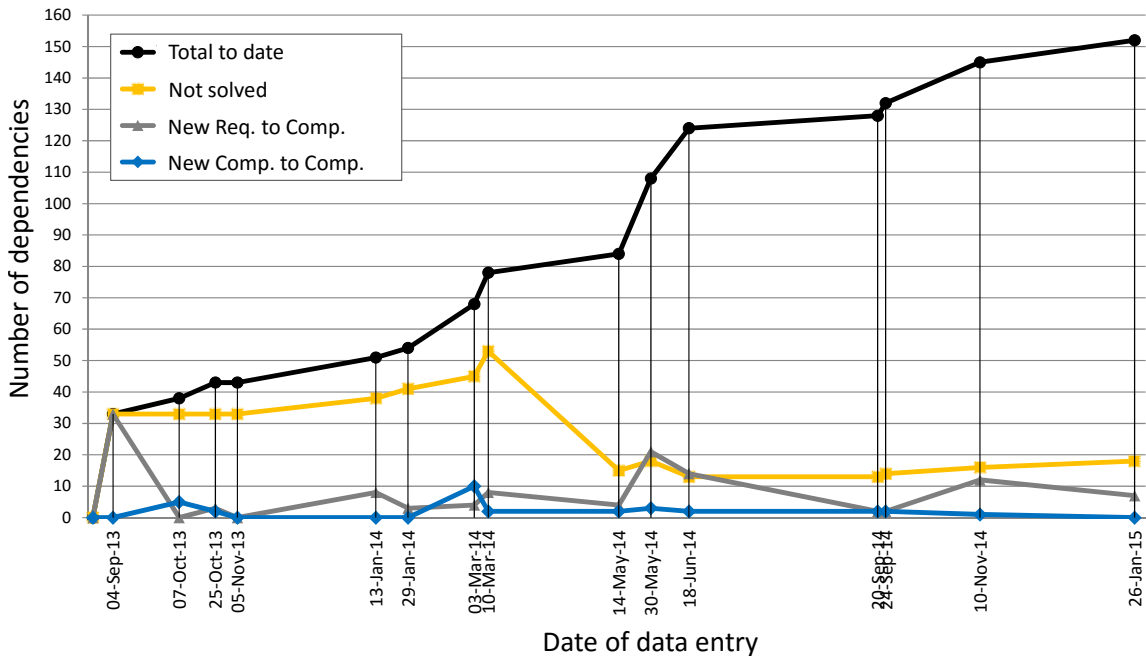

Figure 7. Number of change dependencies with respect to the date of data entry

Table 3. Correlation between change dependencies

	Number of new dependencies	
Dates	Req. to Comp.	Comp. to Comp.
4-Sep-13	33	0
7-Oct-13	0	5
25-Oct-13	3	2
5-Nov-13	0	0
13-Jan-14	8	0
29-Jan-14	3	0
3-Mar-14	4	10
10-Mar-14	8	2
14-May-14	4	2
30-May-14	21	3
18-Jun-14	14	2
20-Sep-14	2	2
24-Sep-14	2	2
10-Nov-14	12	1
26-Jan-15	7	0
Pearson's Correlation Coefficient		-0.211

Figure 8 shows an excerpt of the change propagation network derived from the data collected. The rectangular boxes between components indicate the date of documented change propagation. For example, the change propagation from the 'Electric Motor' (Comp. 18) to the 'Motor Front Plate' (Comp. 36) was documented on the 7th of October, 2013 (illustrated as '071013'). The longest change propagation path in the network was between the 'Battery box lower' (Comp. 7) and the 'Motor Back Support' (Comp. 37). The path is 5-step long affecting 'Bottom frame bars' (Comp. 41), 'Upper frame bars' (Comp. 42), 'Front Mounting Point Winglets' (Comp. 40), and 'Motor Front Plate' (Comp. 36) sequentially along the way. The affected components are shown with bold red casing in Figure 8. Interestingly, it can also be seen from Figure 8 that the 'Electric Motor' (Comp. 18) can be traced as a source of change propagation towards the 'Motor Back Support' (Comp. 37) via the 'Motor Front Plate' (Comp. 36). This suggests that the analysis of change propagation paths should not be based on the date of occurrences alone, and information such as the reason for change propagation has to be captured in order to identify the actual source of change propagation.
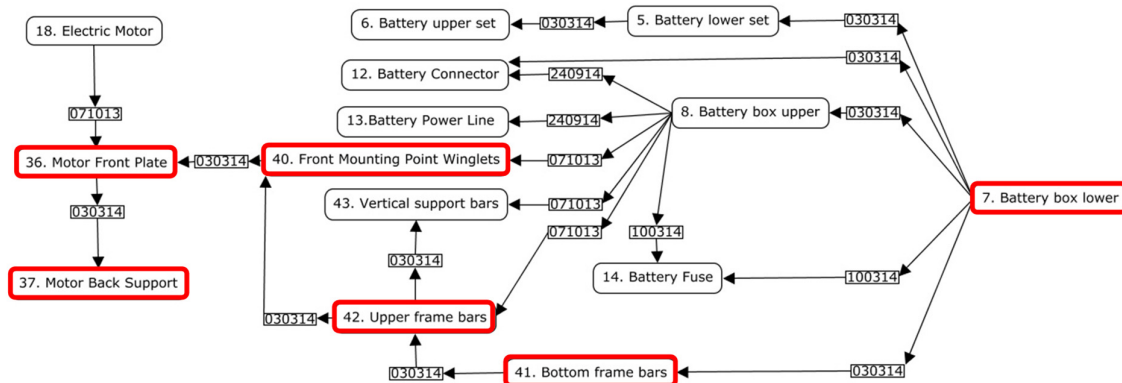

Figure 8. An excerpt of the change propagation network

By reviewing the network, the number of change propagation paths with respect to the number of steps per path can be determined as shown in Table 4. There were 24 unique change propagation paths in total. 67% of them (16 out of 24) consisted of 1 change propagation step, 25% with 2 steps, 4% with 3 steps, and another 4% with 5 steps.

Table 4. Number of change propagation paths with respect to the number of steps per path

No. of steps	No. of paths	Percentage
1	16	67%
2	6	25%
3	1	4%
4	0	0%
5	1	4%
> 5	0	0%
Total	**24**	**100%**

5. Discussions

In this case study, we found that 33% of all changes made were planned (see Table 2). This implies that the design team was vulnerable to emergent changes, with as high as 67% (100% - 33%) of all changes made. The high level of emergent change can be explained by the intense pressure to start designing before the full work plan was developed as the team had to work within tight timeframe and limited resources. Hence, unplanned changes and rechanges need to be added when more is understood from the change requirements along the way. This constraint is however not unique to university/start-up design teams and is commonly practised in concurrent engineering. Nevertheless, unlike mature firms, the design team was also less proficient in establishing the dependencies between the change requirements and the components that need to be changed due to the lack of experience and the lack of information regarding the original design. Indeed, some of the planned changes were not finalised until 3 months into the project. Only 37 of the 50 planned changes were identified right from the start (see Figure 7). Hence, we argue that the modelling of emergent changes is important when designing in a university/start-up context.

Another observation from Figure 7 was that the occurrence of new requirement-component dependencies (i.e. rechanged, unplanned, and planned changes) does not immediately result in new component-component dependencies (i.e. change propagation). One possible explanation is that a delay was required before the need to propagate changes can be acknowledged. However, it is important to point out that there was a brief surge of new requirement-component dependencies on the 30th of May 2014 and the 18th of June 2014, which was not subsequently accompanied by an increase in change propagation. This implies that the number of component-component dependencies (i.e. change propagation) is not correlated to the number of requirement-component dependencies (i.e. rechanged, unplanned, and planned changes), suggesting that the analysis of change propagation between components can be treated separately from the analysis of change requirements.

Lastly, with reference to Table 4, it can be argued that an analysis of the direct dependencies between components at the beginning of the project could have prevented or prepared the design team for 67% of change propagation. Such detection rate may suffice for resource-strapped start-ups who cannot afford to conduct more advanced change analysis or running into unexpected change propagation. Hence, it can be concluded that the use of simple change propagation analysis tools (such as a baseline Design Structure Matrix) can be beneficial for university start-ups when designing new products.

6. Conclusions

Designing in a university/start-up context can pose different challenges as compared to designing in mature firms. There is hence a need to develop appropriate support tools to suit different design contexts. In an attempt to better understand engineering change and its propagation when designing in a start-up environment, this paper examines the evolution of change dependencies during an electrical motorcycle modification project undertaken by a university start-up team. It was found that university/start-up teams can be less experienced in establishing the dependencies between change requirements and the components that need to be changed. In addition, not all planned changes may be identified right from the start due to resource issues. Hence, unplanned changes and rechange are likely to occur during the project when more is understood from the change requirements. This however does not necessarily result in more change propagation as it was revealed that the number of change propagation occurrences is not proportional to the number of requirement-component dependencies (i.e. rechanged, unplanned, and planned changes). It was also revealed that an analysis of the direct dependencies between components at the beginning of projects can prevent or prepare design teams for 67% of change propagation. Such detection rate may suffice for resource-strapped start-ups who cannot afford more advanced change analysis or running into unexpected change propagation. Hence, the use of simple change propagation analysis tools can prove critical when designing in a university/start-up context.

References

De Lessio, M. P., Cardin, M.-A., Astaman, A., Djie, V., "A process to analyze strategic design and management decisions under uncertainty in complex entrepreneurial systems", Systems Engineering, Vol.18, No.6, 2015, pp. 604-624.

de Weck, O., Eckert, C. M., Clarkson, P. J., "Guest Editorial", Research in Engineering Design, Vol.23, No.4, 2012, pp. 265-267.

Eppinger, S. D., Browning, T. R., "Design structure matrix methods and applications", MIT Press Cambridge, MA, 2012.

Fernandes, J., Henriques, E., Silva, A., Moss, M. A., "Requirements change in complex technical systems: An empirical study of root causes", Research in Engineering Design, Vol.26, No.1, 2015, pp. 37-55.

Hölttä-Otto, K., Otto, K. N., Luo, J., "Innovation differences between new venture startups and incumbent firms", Proceedings of the 19th International Conference on Engineering Design (ICED13), Seoul, Korea, 2013, pp. 277-286.

Jarratt, T. A. W., Eckert, C. M., Caldwell, N. H. M., Clarkson, P. J., "Engineering change: an overview and perspective on the literature", Research in Engineering Design, Vol.22, No.2, 2011, pp. 103-124.

Koh, E. C. Y., Caldwell, N. H. M., Clarkson, P. J., "A method to assess the effects of engineering change propagation", Research in Engineering Design, Vol.23, No.4, 2012, pp. 329-351.

Koh, E. C. Y., Caldwell, N. H. M., Clarkson, P. J., "A technique to assess the changeability of complex engineering systems", Journal of Engineering Design, Vol.24, No.7, 2013, pp. 477-498.

Koh, E. C. Y., Forg, A., Kreimeyer, M., Lienkamp, M., "Using engineering change forecast to prioritise component modularisation", Research in Engineering Design, Vol.26, No.4, 2015, pp. 337-353.

Langer, S., Maier, A., Wilberg, J., Münch, T. J., Lindemann, U., "Exploring differences between average and critical engineering changes: Survey results from Denmark", Proceedings of the 12th International Design Conference (DESIGN 2012), Dubrovnik, Croatia, 2012, pp. 223-232.

Loh, A. P., "The Design Centric Programme at the National University of Singapore", Proceedings of the Innovation Practices in Higher Education Expo (I-PHEX), Johor, Malaysia, 2015, pp. 11-13.

Song, C.-Y., Luo, J., Holtta-Otto, K., Otto, K., "Product innovation differences between new ventures and incumbent firms", Academy of Management Proceedings, 2014.

Tang, D., Yin, L., "Using an engineering change propagation method to support aircraft assembly tooling design.", Proceedings of the 6th International Asia Conference on Industrial Engineering and Management Innovation (IEMI), Tianjin, China, 2016, pp. 939-951.

Teegavarapu, S., Summers, J. D., Mocko, G. M., "Case Study Method for Design Research: A Justification", ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, 2008, pp. 495-503.

Weigl, J. D., Koh, E. C. Y., "Impact of engineering change in design education", Proceedings of the International Conference on Advanced Design Research and Education (ICADRE14), Singapore, 2014, pp. 70-72.
Yin, R. K., "Case Study Research: Design and Methods", Sage publications, 2013.

Dr.Edwin Koh,
National University of Singapore, Engineering
Faculty of Engineering, Block E2A, #04-05, 5 Engineering Drive 2 , 117579 Singapore
Email: edwin.koh@nus.edu.sg