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ORIGINAL PAPER

Designing in young organisations: engineering change propagation in a university design project

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Abstract
Engineering change (EC) is an important phenomenon in the design of products and systems, accounting for nearly one-third of the work effort; however, the literature has been focused on mature firms, and few studies have documented the impact of EC beyond them. Hence, we use a case study approach to study EC and its propagation in the context of a university design project as an example of young organisations, and compare it with the existing work done on mature firms. It was found that 33% of the changes that occurred in the case study were planned, and change propagation accounted for 20% of all changes. The propagation of changes was usually one step (67%), and it was concentrated in one independent network (54%). The results were subsequently compared with EC studies done in mature firms, being revealed that EC behaves differently in the context of a university design project; hence, existing change management tools developed to suit mature firms may not be directly suitable for supporting university design projects. The findings from this work can be used as a platform to better understand how EC propagates when designing in young organisations and shape the development of appropriate change management tools.

Keywords Engineering change · Change propagation · Young organisations · Start-ups · Mature firms · DSM

1 Engineering change in different design contexts

Engineering change (EC) is an important phenomenon in the design of products and systems, accounting for nearly one-third of the work effort (Fricke et al. 2000; Langer et al. 2012). ECs can be comprehensibly defined 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). Its propagation, also known as 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). The relevance of EC and ECP is recognised by the design community, which has developed modelling tools to support its prediction and management (de Weck et al. 2012). However, most of the work focuses on EC and ECP within mature firms (see Ahmad et al. 2013; Koh et al. 2013; Tang and Yin 2016), ignoring that younger organisations operate differently (Churchill and Lewis 1983; DeLessio et al. 2015; Hölttä-Otto et al. 2013). For instance, mature firms who redesign their own products will have direct access to information pertinent to their previous designs, while younger organisations that redesign products made by others will have to make numerous assumptions. In addition, without an established supply chain and reputation, it is likely that younger organisations struggle to get support from suppliers during the development of their own designs. Given that these differences are unlikely to be captured by models developed for mature firms (Churchill and Lewis 1983), there is a need to better understand how EC and its propagation can occur beyond a mature firm setup.

In this paper, we seek to address the literature gap about the different ways that EC can occur in young organisations by examining ECP when designing in a university context.

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The work builds on the case study presented in (Koh et al. 2016), which focused on the analysis of changes, and expands the study by evaluating the characteristics of EC and its propagation in two design contexts—mature firms and universities. The design context in this paper can be described by (Jarratt et al. 2011, p. 106) definition of EC: ''An engineering change is an 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.'' Our goal is to establish whether the characteristics of EC and ECP are different enough to require a different set of change management tools.

The remainder of this paper is organised as follows: first, we establish the similarities and differences between the studied contexts; in Sect. 2, we present the research question, method, and evaluation criteria; Sect. 3 develops the case study while Sect. 4 compares our results with previous research; Sect. 5 summarizes and discuss the previous sections, and Sect. 6 concludes this study presenting the most relevant findings.

1.1 Designing in young organisations: universities and start-ups

Globally, there is a growing interest in university-based entrepreneurship. From the academic perspective, 'academic entrepreneurship' and 'technology transfer' are in continuous development (Colyvas et al. 2002; Markman et al. 2005; Meyers and Pruthi 2011; Muscio 2010), showing their specific challenges and how they could complement each other (Clarysse et al. 2011; Gerry et al. 2008; Rasmussen and Borch 2010; Sherwood et al. 2011). From the business side, the market also "permeates" the academia through activities such as entrepreneurship world cups (e.g. http://universityworldcup.com/), world rankings based on collected venture capital (e.g. http://pitchbook.com/news/articles/the-top-50-universities-producing-vc-backed-entrepreneurs), problem-based programs (De Graaf and Kolmos 2003), and project-based programs (e.g. Olin College of Engineering, http://www.olin.edu/). Additionally, since public universities receive significant public resources, society expects concrete benefits of their research (e.g. being responsive to the market and aligned to industry needs Valdivia 2013). Within this environment, it is valid to say that designing in a university context has common and complementary characteristics with designing in a start-up context. However, some differences are unavoidable, starting with the fact that university design projects are constrained by the academic calendar and need to focus on learning outcomes rather than commercial success. Other significant differences are the lack of diversity between students (e.g. similar age and education level), and less mature dynamics (e.g. clear objectives with no hidden agendas) (Ensley and Hmieleski 2005). Nevertheless, although there are limitations, university design projects with an entrepreneurial focus provide a suitable starting point to study engineering change and its propagation when designing in young organisations.

1.2 Designing in start-ups and mature firms

In general, start-ups are more evolutionary, dynamic, and coupled with significant uncertainty than mature firms (DeLessio et al. 2015). Table 1 shows how relevant topics are generally perceived for each context.

These differences generate questions about the validity of using design tools developed for mature firms in young organisations. For example, considering Table 1 'innovation degree', a mature firm that needs to meet new requirements will probably modify their existing product, while a start-up is more likely to look for a new approach. Both ways imply different design challenges, and consequently, EC and ECP may occur differently.

2 Research question and validation method

In an effort to establish whether there is a need to develop a different set of change management tools specifically for young organisations (universities and start-ups), this work examines the characteristics of EC and ECP when designing in a university context and contrasts them with those described in a mature firm context. Therefore, we attempt to answer the following question:

> How might the characteristics of engineering change and its propagation differ between designing in a university context and a mature firm context?

To answer this question, a case study on a university design team was carried out. The case study method is defined as "an empirical inquiry that investigates a contemporary phenomenon within its real life context" (Yin 2013). In our work, engineering change and its propagation cannot be separated from real life, since their behaviour depends on each particular design context; consequently, to utilise a case study is appropriate.

The following sub-sections describe the case study design (2.1), the procedure to prepare and analyse the data collected (2.2), and the framework for cross-case evaluation (2.3). Figure 1 presents the basic structure that this paper follows, based on the method described by (Yin 2013) and (Teegavarapu et al. 2008).

Table 1 Differences between mature firms and start-ups

Topic	How it is manifested in start-ups or mature firms	References
Innovation degree	Mature firms are likely to succeed with imitative entries into new markets, while start-ups are often successful in "disruptive technologies": low cost, simplified design, increased ease to access, and user-friendly. In addition, start-ups tend to show a higher level of innovation in their products	Bommer and Jalajas (2004); Christensen (2013); Klepper (2007); Song and Otto (2014); Song and Parry (2010)
Research and development	Mature firms usually have stronger R&D capabilities (e.g. equipment, experienced teams) that allow them to develop sophisticated technologies and operate with higher efficiency in general. Start-ups lack of experience and financial resources limits their projects' complexity	Dougherty (2001); Haltiwanger and Spletzer (1999); Hurst and Lusardi (2004); Schumpeter (2013); Shane (2009); Shane (2008)
Resilience/stability	Mature firms are known in the market and can deal with uncertainty, while only a small fraction of start-ups survive and thrive in the long term (22% after 5 years)	Song and Song (2010); Song and Halman (2008)
Organisational inertia	Mature firms tend to avoid trials and changes and must satisfy existing customers and suppliers. Start-ups are more likely to introduce radical innovations, which can also attract more innovators	Christensen (2013); Gilder (1988); Song et al. (2014)
Available assets	Mature firms aim to exploit its existing resources and capabilities while simultaneously developing new corporate assets for opportunities, which limit their potential paths	Dierickx and Cool (1989); Stieglitz and Heine (2007)
Marketing	Start-ups have more challenges in their products adoption and diffusion, applying often low cost benchmarking and informal ways to gain market knowledge	Marion and Friar (2012); Song et al. (2010a, b)
Customer relation	Start-ups tend to develop products for niche markets, producing small quantities for a few customers. This makes critical to establish close relationships since the design stage	Bommer and Jalajas (2004); Lau and Yam (2010)
Suppliers	Start-ups usually look for suppliers, and their involvement tends to be positive in product differentiation and success. However, they tend to receive low support because of their "minor client" status	de Oliveira and Kaminski (2012); Lau et al. (2010); Song et al. (2010a)
Cooperation with other firms	Start-ups tend to cooperate with established firms to benefit from their reputation, customer and supplier relationships	Dowling and Helm (2006); Heirman and Clarysse (2007)
Governmental support	Technological start-ups can benefit from government support	Doh and Kim (2014); Heirman and Clarysse (2007)

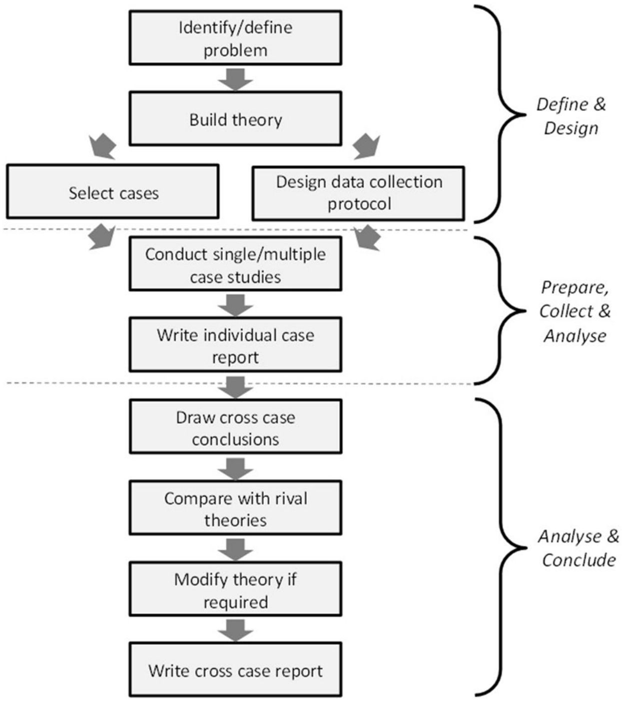

Fig. 1 Case study method, adapted from (Teegavarapu et al. 2008; Yin 2013)

2.1 Define and design: case study

The method selected has three general phases; the first stage focuses on how the case study will be carried out (define and design, Sect. 2 of this paper); the second stage documents and analyses the particular case study (prepare, collect, and analyse, Sect. 3 of this paper); finally, the third stage compares the obtained results with other studies, to establish valid conclusions (analyse and conclude, Sects. 4 and 5 of this paper).

The selected case study is a university design project conducted by a multi-disciplinary team, which was carried out within the Design-Centric Programme at the National University of Singapore (Loh 2015). The team aimed to commercialise the design and operated with tight deadlines, limited resources, low bureaucratic inertia, and low restriction on suppliers. These characteristics satisfy Yin's recommendations (Yin 2013, Fig. 1.2), offering a suitable context to examine the occurrence and propagation of EC in a university design context. Additionally, several of the case study characteristics can be related to the typical challenges that young organisations—in general—have to deal with, satisfying our interest in progressively develop a better understanding of EC beyond mature firms.

EC and ECP were documented through matrices and interviews to allow its analysis as described in Sect. 2.2. To compare results with research done in mature firms, five criteria will be discussed, namely documentation of change request, change resistance and cancelled changes, changes evolution, propagation length, and changes distribution (definitions in Sect. 2.3). These criteria were developed after reviewing the related literature (see Table 7) while planning the present study.

2.2 Prepare, collect and analyse: DMM, DSM, and interviews

During this stage (prepare, collect and analyse), the objective is to study ECs and their propagation. ECs on components are initiated in response to requirements since if there is no requirement, no change is needed. ECP between components occurs when an EC cannot be completed without changing more components. To list and analyse these relations, we utilised a Domain Mapping Matrix (DMM) for the requirement–component relations and a Design Structure Matrix (DSM) for the component–component relations. Both matrices are frequently used to study change and its propagation in different circumstances (Browning 2001; Chiriac et al. 2011; Koh et al. 2012, 2015; Steward 1981). Complementarily, both matrices are part of the students' program, thus we considered them valid and easy to be used by the team.

In brief, a DMM registers in a rectangular matrix the dependencies between elements of different domains (Danilovic and Browning 2004), allowing visualisation of multiple relations. In this work, the change requirements were mapped to the components targeted for change using Table 2 entry code, thus including the change status simultaneously, as presented in Fig. 2. For example, it can be seen that Component 2 has completed a Rechange initiated in Requirement A, while a Planned change originated in Requirement B is still in progress. This modification allowed tracking the change status evolution between requirements and components.

Similarly, a DSM is a square matrix that relates elements within the same domain (Eppinger and Browning 2012). For example, Fig. 3 shows that component 1 is affected by component 3, component 2 is affected by components 1 and 4, component 3 is affected by component 4, and component 4 is affected by component 1. Both matrices were updated regularly to analyse patterns and tendencies.

Finally, we interviewed the team supervisors to answer two questions: how were change requests documented in the project? How were change requests reviewed in the project? The answers allowed us to obtain information about the dynamics of the team that were not available in the matrices and judge if more development was necessary to compare results with mature firms.

Table 2 Codes associated to every change status of dependencies

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

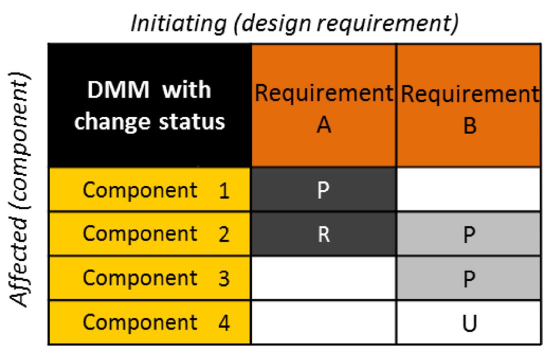

Fig. 2 DMM linkage. The matrix presents the relation between components and its status, following Table 2 logic

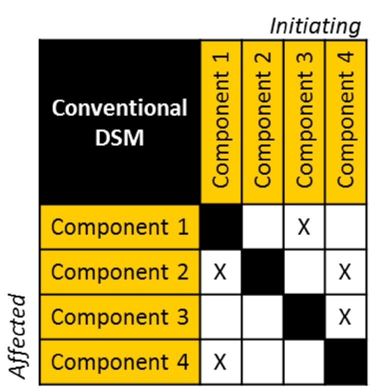

Fig. 3 Mapping relations between components in a DSM. For example, it can be noted that component 1 affects directly components 2 and 4 (one step)

2.3 Analyse and conclude: comparison with existing work

To determine how different EC and ECP are between contexts, the results of our case study will be compared with the results obtained in relevant case studies documented in the literature (Sect. 4). Five evaluation criteria are discussed:

- Cr1. Documentation of change requests: how the organisation collects and retrieves its change requests.
- Cr2. Change resistance and cancelled changes: stakeholders reaction to change requests and the number of cancelled changes
- Cr3. Changes evolution: variation of the change quantity through time.
- Cr4. Propagation length: quantity of components that change as a consequence of its direct or indirect relation with another component.
- Cr5. Changes distribution: determine the existence of any tendency or pattern in change distribution.

We defined these criteria because standard parameters are not readily available to facilitate direct comparison or a robust statistical analysis with existing work (even within existing work). To facilitate reading, the criteria are listed following their appearance during the case study results and analysis (Sect. 3.2).

3 Case study: an electrical motorcycle modification project

As mentioned in Sect. 2.1, the case studied is a university design project conducted by a multi-disciplinary team, as a part of the Design-Centric Programme of the National University of Singapore (Loh 2015). More specifically, it involves the modification of a standard combustion motorcycle towards electrical drive. The modified motorcycle, referred to as E-Bike (see Fig. 4), required conceptual and practical design work to achieve the final objective of commercialization (details in Teo et al. 2013; Weigl 2014; Weigl and Koh 2014). A milestone during the recorded period was the team participation in the World Advance Vehicle Expedition (WAVE) on May 29th, 2014 (Team Frogworks, http://www.wavetrophy.com/en/history/wave-2014/teams/). Unlike traditional capstone or credit students projects, in this project the supervisors were the ones who were responsible for the results, having to satisfy the requirements of all the involved (university, race organisation, and sponsors).

The work team consisted of two supervisors with complete autonomy in deciding the direction and management of the project, and seven undergraduate students. It

Fig. 4 The modified motorcycle (E-Bike) on exhibition

is important to mention that the researchers of this study did not participate in any of the design activities, ensuring data integrity. The E-Bike team aimed to commercialise the design while dealing with tight deadlines, limited resources, low bureaucratic inertia, and low restriction on suppliers, all characteristics similar to those associated with start-ups (see Table 1). For example, the race participation defined a non-flexible milestone, where the team had to deliver results with the given resources. If we use the classification proposed by (de Oliveira and Kaminski 2012), on which small and medium industrial enterprises are listed in four levels of maturity (higher level, more mature), it can be said that the team presented characteristics from the first and second levels of maturity, specifically 'organisation for product development', 'initiative to cooperate with suppliers', and 'acknowledge the importance of new products and new markets'.

3.1 Data collection

The collection of data began in September 2013 and ended in January 2015, totalizing 15 reports. The data collected include the change requirements formulated and the components changed, together with the associated dates and observed dependencies. The data were captured from the project supervisors of E-Bike (the second and the third authors of this paper) by the researchers of this study (the first and the fourth authors of this paper) using DMM and DSM conventions in Microsoft Excel. According to the project supervisors, the change requirements formulated contribute directly to the plan to commercialise the E-Bike and they remained the same throughout this work. Due to resource limitation, the impact of change such as the additional workload incurred by the team was not captured in this work. The complete list of change requirements captured is as follows:

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		

Fig. 5 An excerpt of the requirement–component relations observed

A. Provide a professional engineering look (with the electrical drive installed)
B. Add a data acquisition system
C. Increase range and reliability
D. Increase driving performance
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 Fig. 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, Fig. 5 shows an excerpt of the requirement–component mapping captured on the 24th of September, 2014 (1 year into the project) using the entry codes explained in Table 2. It can be seen that component '4.12V system main switch' needed to be changed to address requirement 'A.Provide a professional engineering look (with the electrical drive installed)'. 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 '1.12V DC-DC converter' to address the requirement 'D.Increase driving performance' during the project and the change was ongoing at the time of data entry (Entry code = U, Light grey cell). Component '8.Battery box

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										

Fig. 6 An excerpt of the component–component relations observed

upper' was rechanged to address requirement D as well, and the change was completed prior to the time of data entry (Entry code = R, Dark grey cell). Component '19.Sprocket' 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).

Similarly, Fig. 6 shows an excerpt of the change propagation between components, 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 '1.12V DC–DC converter' had propagated to the '2.12V Fuse' and '3.12V Fuse holder'. Changes made on the '5.Battery lower set' had also propagated to '6.Battery upper set'. 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.

3.2 Case study results

Based on the data collected, there were 152 changes recorded. 50 changes were planned at the beginning of the project while the other 102 changes emerged later. Out of them, 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. From the total of 152 changes, 8 were cancelled during the project (6 planned changes and 2 unplanned changes). Table 3 shows the percentage breakdown between the change categories. Complementarily, as explained in Sect. 2.2, we interviewed the team supervisors to obtain information unavailable in the matrices. When asked about the documentation of change requests, the supervisors explained to us that all changes were registered using a DSM, without further documentation. Regarding the review of change requests, there was no formal review

Table 3 Change categories breakdown

Total changes	Planned changes	Unplanned changes	Rechanged changes	Change propagation	Cancelled changes
152	50	55	16	31	**8**
100%	33%	36%	11%	20%	**5%**

Cancelled changes are presented in bold since they are redundant

process either, mostly because it was not considered necessary since the team had a positive attitude towards change, as it understood the need of it in a design project. The way that change requests were documented, the change resistance, and the number of cancelled changes are further discussed in Sect. 4, to examine the similarities and differences between designing in a mature firm context and designing in a university project context (first and second criteria).

To visualise the evolution of the requirement–component relations, we constructed network diagrams that linked requirements and components through the date when each relation was accounted in the DMM, indicating also the change category (see Fig. 7). For example, on September 4th, 2013, it was registered the planned relation between requirement "B. Add a data acquisition system" and components 34, 45, 46, 47, 48, and 49. We also used similar diagrams to visualise the component–component propagation data captured in the DSMs at different points in time, two of them presented in Fig. 8. For example, on October 7th, 2013 it was established that component '28. Brake switch front and back' was affected by component '25.Motor controller' (one-step), which increased its propagation on May 30th and September 20th, 2014 (see Fig. 8 right), affecting directly components '24.Motor cabling', '26.Motor controller control wiring', '29.Motor controller mounting', and indirectly component '27. Electronic throttle' (two-steps). The evolution of changes during the design project is further discussed in Sect. 4 to examine the similarity and differences between designing in a mature firm context and designing in a university project context (third criterion).

Figure 9 shows the number of new requirement–component relations alongside with the number of new component–component relations across different time intervals (evolution). It can be seen that the number of new component–component relations (i.e. change propagation) did not increase with the number of new requirement–component relations (i.e. rechanged, unplanned, and planned changes). In fact, with reference to Table 4, the Pearson's correlation coefficient between the two sets of data were found to be − 0.211, implying no correlation.

Looking at Fig. 9, it is possible to see three stages between the 'Total to date' and the 'Not solved' changes curves. Initially, both increase their value simultaneously,

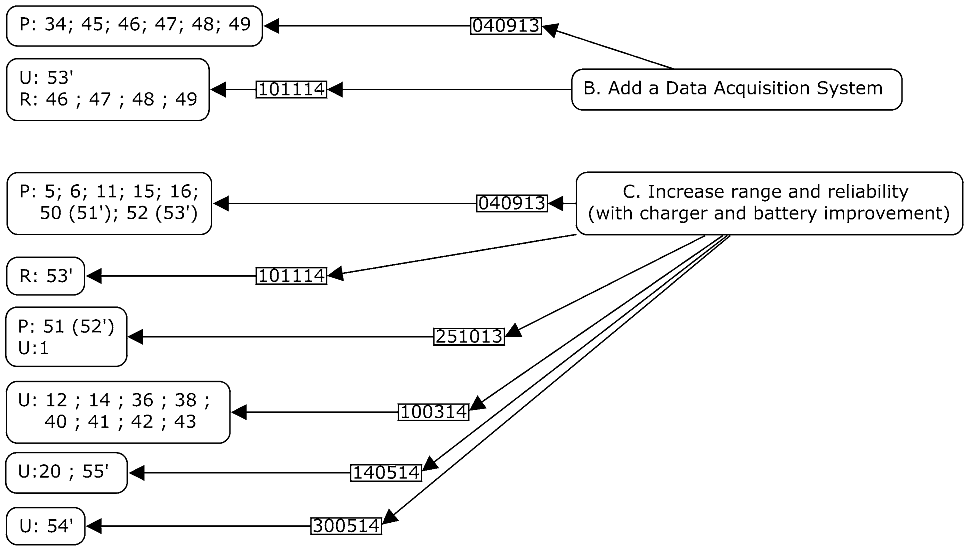

Fig. 7 Sample of requirement–component relations for requirements B and C. e.g. '040913' means 4th of September, 2013

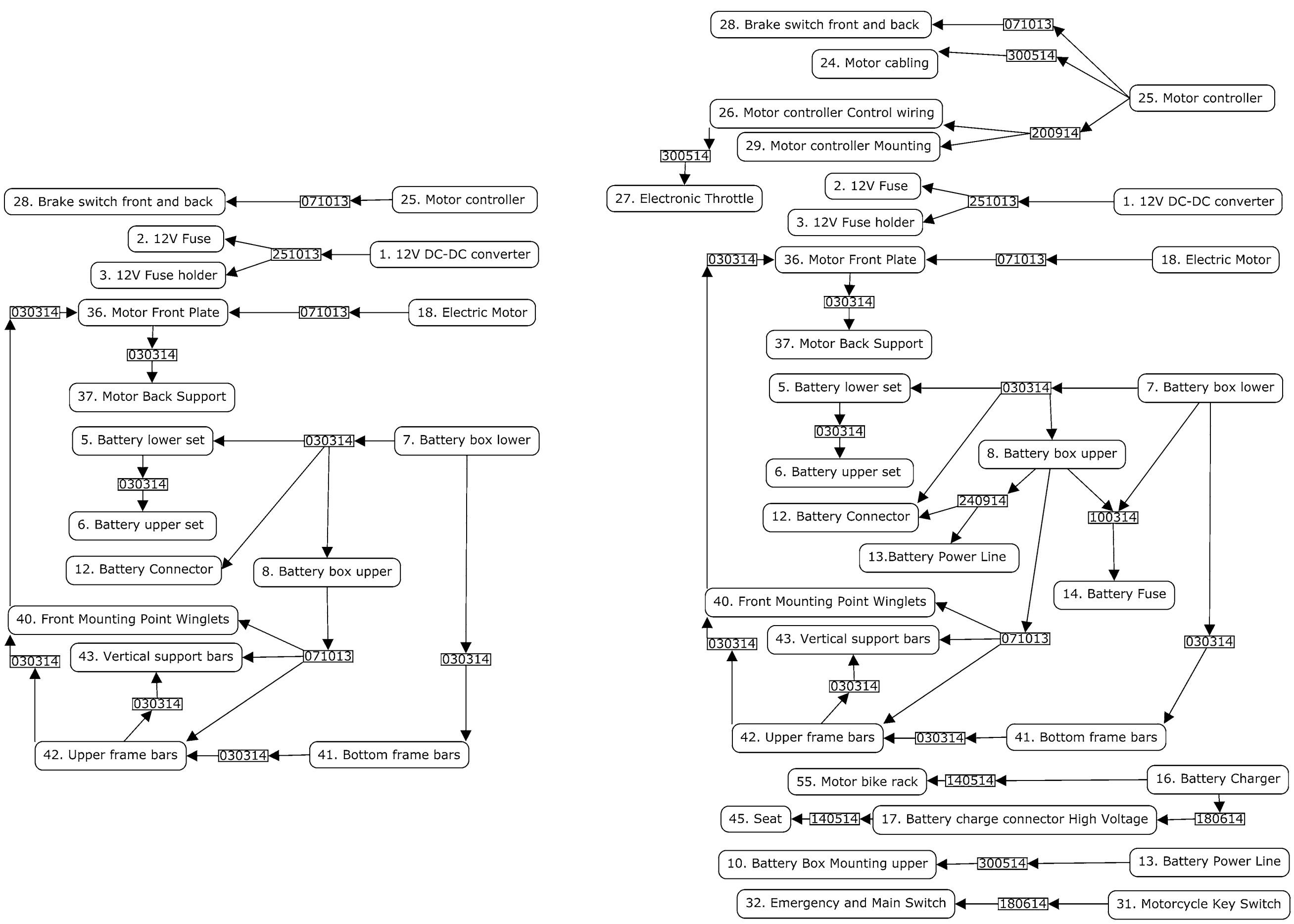

Fig. 8 Component–component relations at 03/03/2014 (left) and 24/09/2014 (right). It can be visualised the ECP through time

implying that more changes emerge but not as many are addressed (from September 4th, 2013, until March 10th, 2014); subsequently, while getting closer to the WAVE race the total number of changes increases moderately while most of them are addressed (between March 10th, 2014, and May 14th, 2014); finally, the total changes

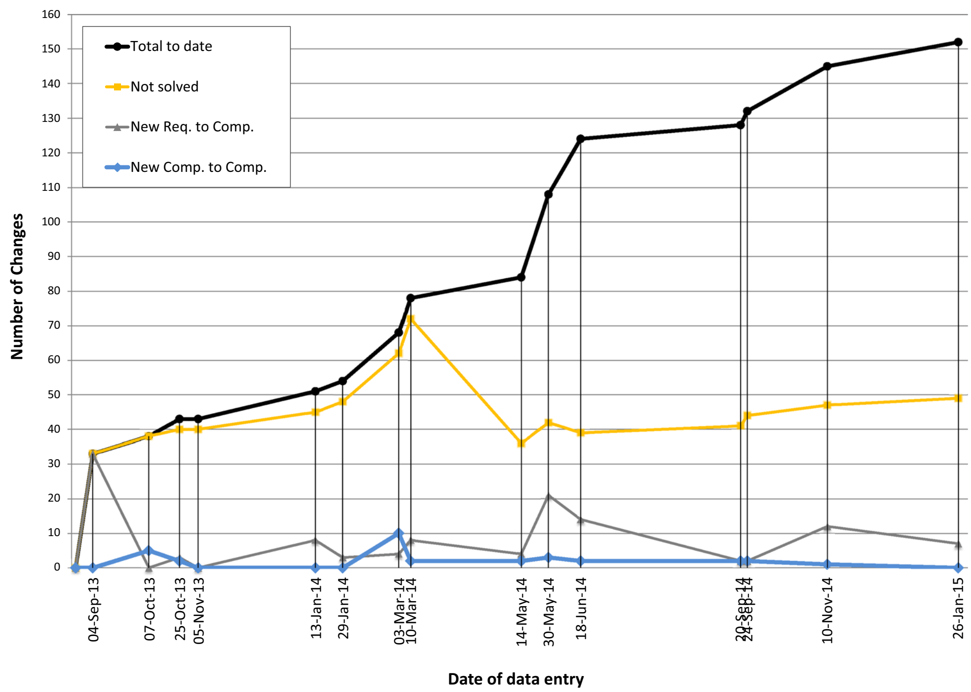

Fig. 9 Number of change relations with respect to the date of data entry

Table 4 Correlation between ECs and ECP

Dates	Number of new changes	
	REq. to Comp	Comp. to Comp
04-Sep-13	33	0
07-Oct-13	0	5
25-Oct-13	3	2
05-Nov-13	0	0
13-Jan-14	8	0
29-Jan-14	3	0
03-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
l0-Nov-14	12	1
26-Jan-15	7	0
Pearson's correlation coefficient		− 0.211

continue increasing while there is a new increase in the number of changes addressed. This information is presented with more details in Table 5; for example, on October 25th, 2013, three new changes were registered, giving a total of 36 changes of which 33 were pending (92%). These results are discussed further in Sect. 3.3 and compared with mature firms in Sect. 4.3.

Regarding component–component relations, Fig. 10 shows an excerpt of the final network, including the longest ECP path. It is five-step long and starts at component '7.Battery box lower', affecting '41.Bottom frame bars', '42.Upper frame bars', '40.Front Mounting Point Winglets', '36.Motor Front Plate', finishing in '37.Motor Back Support'. Affected components are shown with bold red casing. It can also be seen that component '18.Electric Motor' can be traced as a source of change propagation towards component '37.Motor Back Support' via component '36.Motor Front Plate'.

Reviewing the network, the number of change propagation paths with respect to the number of steps per path was determined, which is shown in Table 6. From the 24 existing paths, 67% were one step, 25% two steps, 4% three steps, and 4% five steps. The propagation length of changes during the design project is further discussed in Sect. 4 to examine the similarity and differences between designing in a mature firm context and designing in a university project context (fourth criterion).

Most of the propagation were either one or two steps, while the exceptions were part of a group initiated by component '7.Battery box lower' (see Fig. 10). This contributed to the concentration of dependencies in a small number of independent change propagation networks (ICN), as presented in Fig. 11. Our condition to define an ICN was to have all its components connected, either directly or indirectly. This revealed that from seven ICNs, most of the components and their paths were concentrated ICN-1, with 13 propagation paths, 54% of the total (24, see Table 6). The change distribution of the design project is further discussed

Table 5 List of generated reports by date, presenting the state of changes and the stages observed

Report date	Changes				Average of changes addressed by stage	Duration
	New	Total	Pending	Percentage pending		
2013-09-04	33	33	33	100	Pre-race 8% addressed	187 days
2013-10-07	0	33	33	100		
2013-10-25	3	36	33	92		
2013-11-05	0	36	33	92		
2014-01-13	8	44	38	86		
2014-01-29	3	47	41	87		
2014-03-03	4	51	45	88		
2014-03-10	8	59	53	90		
2014-05-14	4	63	15	24	Race 77% addressed	81 days
2014-05-30	21	84	18	21		
2014-06-18	14	98	13	13	Post-race 86% addressed	241 days
2014-09-20	2	100	13	13		
2014-09-24	2	102	14	14		
2014-11-10	12	114	16	14		
2015-01-26	7	121	18	15		

The pending changes were determined dividing the not solved ones by the total

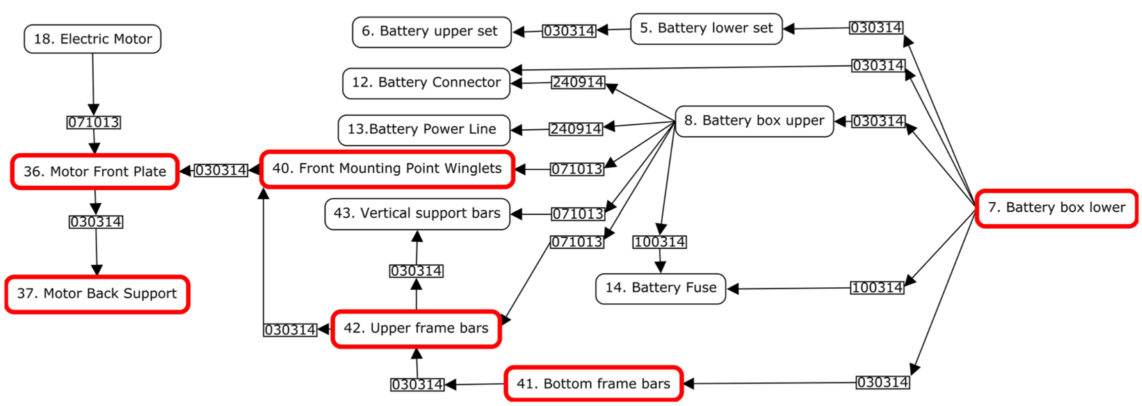

Fig. 10 Extract of the final change propagation network

Table 6 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

in Sect. 4 to examine the similarity and differences between designing in a mature firm context and designing in a university project context (fifth criterion).

3.3 Case study discussion

As presented in Table 3, 33% of all changes made were planned, implying that the design team was vulnerable to emergent changes 2 out of 3 times. This 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 a tight timeframe and limited resources. Hence, unplanned changes and rechanges need to be added when more was understood from the change requirements along the way. This constraint is however

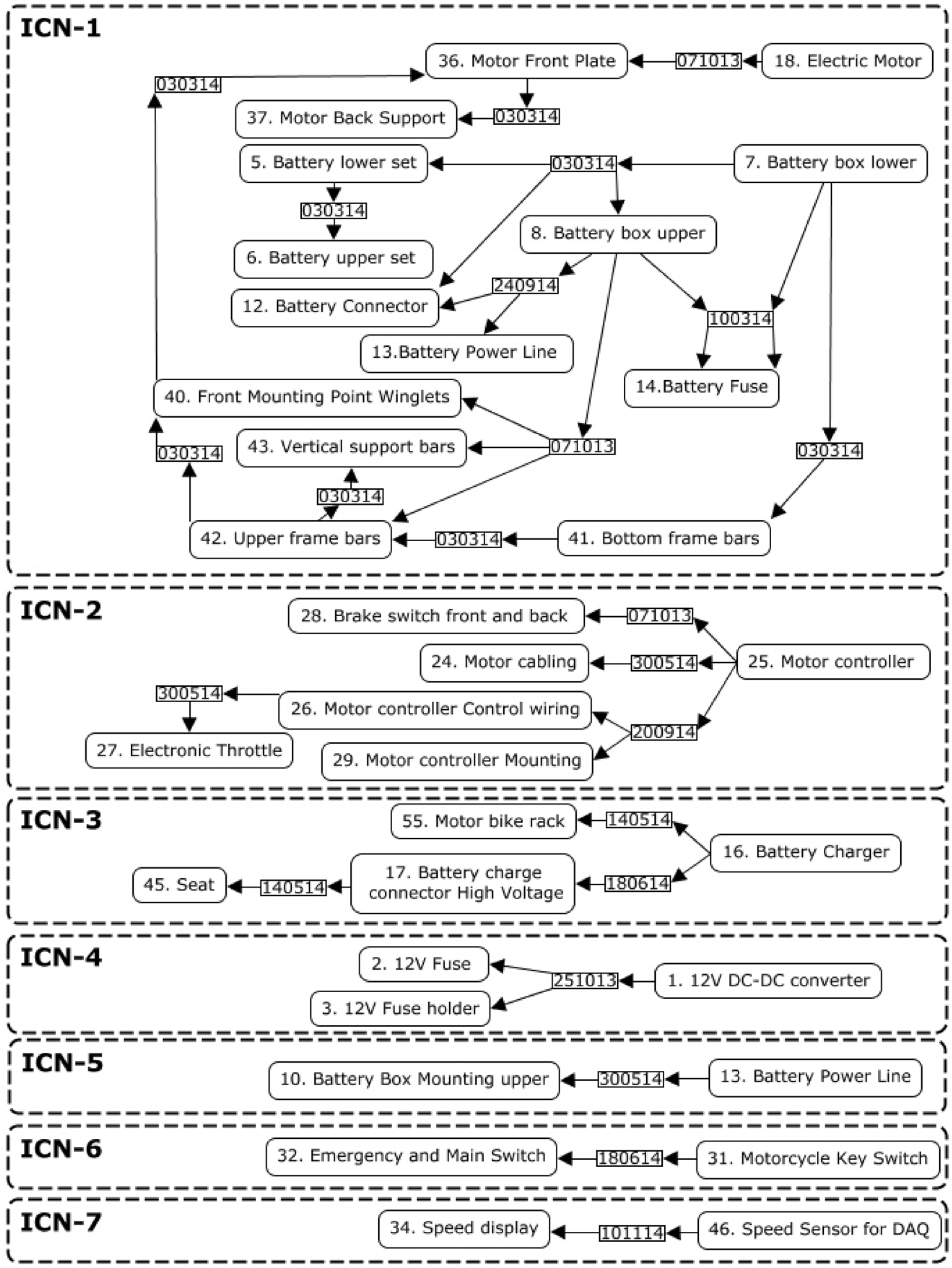

Fig. 11 Final propagation network, showing the distribution of the relations between components and the independent change propagation networks (ICN)

not unique to university design project teams and is commonly practised in concurrent engineering. Additionally, the E-bike team's inexperience and lack of information delayed the establishment of relations between change requirements and components. Indeed, only 37 of the 50 planned changes were identified right from the start (see Fig. 9), with some of the planned changes finalised 3 months into the project.

The data suggest that the vulnerability to unplanned changes was the cause of the three stages presented in Table 5. During the pre-race, the number of changes addressed was on average 8%, while getting closer to the race it increased to 77% because most of the changes were necessary to participate. During the post-race stage, the E-Bike increased the addressed changes to 86%, which was maintained until the end of the reported period.

Another observation is that the occurrence of new requirement–component relations (i.e. rechanged, unplanned, and planned changes) does not necessarily result in new component–component relations (i.e. change propagation). One explanation could be that a delay is required before the need to propagate changes can be acknowledged, but looking at Table 4 it can be noted that there was a surge of new requirement–component dependencies on the May 30th and June 18th, 2014, which was not subsequently accompanied by an increase in change propagation. In fact, the Pearson's correlation coefficient between the two sets of data was −0.211

(no correlation), suggesting that the analysis of change propagation between components can be treated separately from the analysis of change requirements.

With reference to Table 6, 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 (92% considering two-step propagation). Such detection rate may suffice for resource-strapped young organisations who cannot afford to conduct more advanced change analysis or running into unexpected change propagation. In addition, as shown in Fig. 11, 54% of the relations between components were concentrated in one independent change propagation network (13 out of 24 relations), and if we also include the second most numerous ICN, the percentage reaches 71% (17 out of 24 relations). The previous shows that change propagation is mostly within isolated influential networks, and how the use of simple change propagation analysis tools (such as a baseline Design Structure Matrix) can be beneficial for the design of products in a university context.

4 Comparison with existing work (mature firms)

To compare our results with previous research, the most complete paper is Giffin et al. (2009), since it can be compared in four of the five criteria (see Sect. 2.3). To examine if there is a consistent behaviour within mature firms, we included additional papers for each criterion, as presented in Table 7.

4.1 Cr1. Documentation of change requests

In Giffin et al. (2009), the data were stored in a company developed configuration management system. Siddiqi et al. (2011) recorded changes through Design Change Notices (DCN), which comprised 30 different fields including sequence number, date raised, final approval status (approved, rejected or withdrawn), and final approved cost. This is similar to the Engineering Change Notifications (ECNs) presented in Morkos et al. (2012), which registered in detail the relevant data, such as the change originator, the project, the reason for the change, and a status of approval or rejection (see Fig. 12).

In the E-bike, changes were discussed and approved verbally by the supervisors, leaving no documentation behind (this should not be confused with the documentation of the research, which was done in Excel spreadsheets after the change approval, following Figs. 5, 6 logic). This difference was expected since mature firms usually require more complex procedures to handle bigger projects. However, the immediate verbal approval and the fact that ignored proposals were not registered expanded our perceived distance between the two contexts.

4.2 Cr2. Change resistance and cancelled changes

Investigating how different areas behave in front of change, Giffin et al. (2009) defined two ratios, the change acceptance index (CAI) and the change reflection index (CRI). They found a wide spectrum of behaviour, ranging from "perfect acceptors", where all the requested changes were executed, and "perfect resistors", where no changes requested were accepted. In general, resistors categories are the result of management policies that make easier to make alternative changes than the proposed, reflecting the change in other components (Eckert et al. 2004). Regarding cancelled changes, Giffin et al. (2009) indicated that they were 16%

Notification date:	**Change notification #:**
Finish date:	**Approved [ ] Rejected [ ]**
Customer:	**Customer ID#:**
Project:	**Customer Signature:**
Comments:	
Change details	
Responsible: Origin (internal, client, other): Estimated schedule delay: Brief description:	
Impact: explanation and costs	
Engineering:	$
Programming:	$
Clerical:	$
Fabrication:	$
Materials:	$
Others:	$
Total cost	**$**

Fig. 12 Example of change register form used in mature firms, adapted from Morkos et al. (2012)

Table 7 List of criteria, and the papers related to each one

Cr1.Documentation of change requests	Cr2.Change resistance and cancelled changes	Cr3. Changes evolution	Cr4. Propagation length	Cr5. Changes distribution
Giffin et al. (2009)	Giffin et al. (2009)	Giffin et al. (2009)	Clarkson Simons, and Eckert (2004)	Giffin et al. (2009)
Siddiqi and Keller (2011)	Morkos and Summers (2012)	Siddiqi et al. (2011)	Pasqual and de Weck (2012)	Suh and Chang (2007)
Morkos et al. (2012)	Fernandes and Moss (2014)			

of the total (5860 over 36,396). In Fernandes et al. (2014) study about root causes of requirements change, it is not possible to determine the proportion of cancelled changes (referred to as "removals") since no absolute values are included, but from their figures it can be appreciated that cancelled changes were above 10% on four of their five reports, reaching 40% in the fourth one. Finally, Morkos et al. (2012) informed an engineering change notifications (ECNs) rejection of 10 out of 16, being the listed reason 'change in customer requirements'. Although Fernandez and Morkos studies are focused on the requirements, they showed the similarity between mature firms.

In the E-bike, within the project original limits, there was no change resistance (see Sect. 3.2), without showing any of the additional dimensions of mature firms (such as component ownership within the firm and with suppliers, see Table 1, Christensen 2013; Song et al. 2014). The team had a positive attitude as it understood that engineering change is fundamental in a design project, and thus they expected it. Regarding the cancelled changes, they reached a 5% (8 over 152 see Table 3) and were mostly funding related (as suggested at Table 1, last row). The sample size is valid, surpassing the minimum of 73, while our confidence interval goes from 1.7 to 8.7% due to our cancelled proportion of $8/156 = 5.1\%$, using typical variables $\alpha = 0.05$; precision = 5%. For calculations, see for example, Triola (2010, p. 366), Dhand and Khatkar (2014), or Montgomery (2009, p. 123).

To compare, we calculate the same indexes for Morkos and Giffin: Morkos requires a sample size of 363 (due to their cancelled proportion of $10/16 = 62.5\%$), while Giffin needs 207 (cancelled proportion of 16.1%). Since Morkos sample is insufficient we can only compare with Giffin, who has a confidence interval of 15.7–16.5%. We can observe that there is no overlap between our confidence interval and Giffin's; in fact, in the worst-case scenario (8.7 vs. 15.7%) Giffin almost double our results, supporting that engineering change and its propagation differ between a young context and a mature one (see Table 8).

Table 8 Cancelled changes comparison between available studies

	E-Bike	Giffin	Morkos
Sample size validity	73	207	363
Sample size study (total changes)	156	36,396	16 (invalid)
Cancelled changes	8	5860	–
P	0.051	0.161	–
α	0.050	0.050	–
$Z_{\alpha/2}\sqrt{\frac{p(1-p)}{n}}$	0.0346	0.0038	–
Inferior limit	0.017	0.157	–
Superior limit	0.086	0.165	–

4.3 Cr3. Changes evolution

Giffin et al. (2009) present the number of new change requests written per month over the duration of the project. The shape obtained was classified as a "late ripple" following the criteria proposed by Eckert et al. (2004) (see Fig. 13). Siddiqi et al. (2011) investigated the dynamics of change volume by plotting the number of 'design change notices' raised quarterly. Their graph also showed a 'ripple', earlier this time, which is considered a sign of well-understood, predictable processes.

The evolution of changes in the E-bike did not fit the 'ripple' shape being closer to an 'avalanche', where the deadline to consider was the race participation (see Fig. 14). Since the E-bike team could not establish all the requirements–components relations right from the

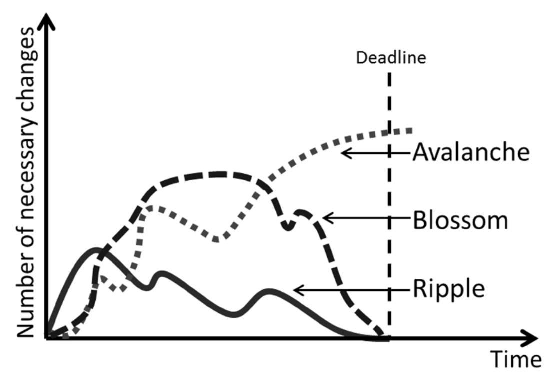

Fig. 13 Change effort and system behaviour, adapted from Eckert et al. (2004)

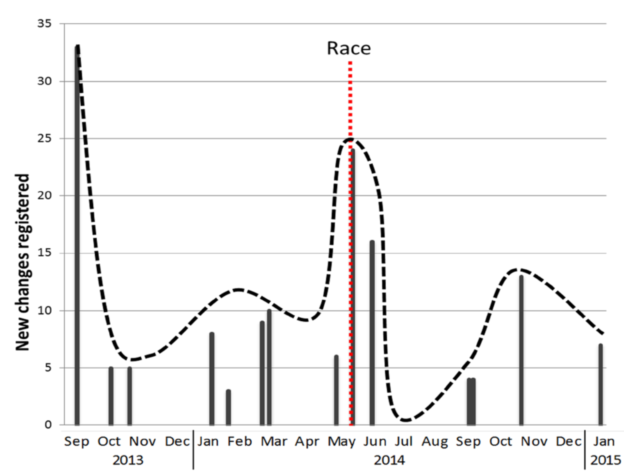

Fig. 14 Changes registry for the E-bike

start, this may have led to the accumulation of unplanned changes and rechanges more likely to happen closer to the milestone. This capacity of establishing early the relations between requirements and components could be the reason why mature firms in similar situations (e.g. toys development for Christmas, engine improvement due to new regulations) could expect a 'ripple' pattern, despite the unavoidable last-hour changes. After the race, the main objective of commercialising the E-bike required new changes, which did not show any pattern until the end of the reported period.

4.4 Cr4. Propagation length

Using the data documented by Giffin et al. (2009), Pasqual and de Weck (2012) found that most of the changes were not originated in propagation, and that propagation was mostly concentrated in one step ('generation' in their study), with a low number of cases going beyond three-step propagation (see Fig. 15, left). It is not clear which method they used to determine their components' granularity.

To compare the E-bike results with theirs, we present our data on a logarithmic scale (see Fig. 15, right). It is possible to observe that there are differences in magnitude—expected—and behavior: the E-bike shows a stronger variation from 0-step (changes not caused by propagation) to one step, and no relevant propagation beyond two steps. This goes against the expectation that 'inexperienced' students—although guided—should have a deep propagation cycle that generates multiple changes. Considering absolute numbers, propagation over two steps was an exception in our study, but common for Pasqual and de Weck (2012), which was probably caused by the higher design complexity.

4.5 Cr5. Changes distribution

Giffin et al. (2009) analysed their data using graph theory, concluding that change activity was not uniformly distributed throughout the system but concentrated in 5 of 46 areas that featured the 60% of implemented changes. Complementarily, in their study about flexible product platforms (Suh et al. 2007) also found that there are critical components and paths for embedding flexibility, and that this is the most critical and difficult phase in incorporate flexibility to deal with uncertain future demand and specification changes.

Both cases are similar to what we observed in the E-Bike. As shown in Sect. 3.2, there is one independent change propagation network that concentrates 54% of the relation paths, and the determination of the critical components (multiple relations and depth) was a critical step to deal with the required changes.

5 Summary and discussion

In relation to the research question (How might the characteristics of engineering change and its propagation differ between designing in a university context and a mature firm context?), we observed that only one criterion behave similarly in mature firms and E-bike. The other four criteria were significantly different.

5.1 Cr1. Documentation of change requests

Mature firms follow a procedure oriented to improvement through control. In the E-bike, the procedure was oriented to

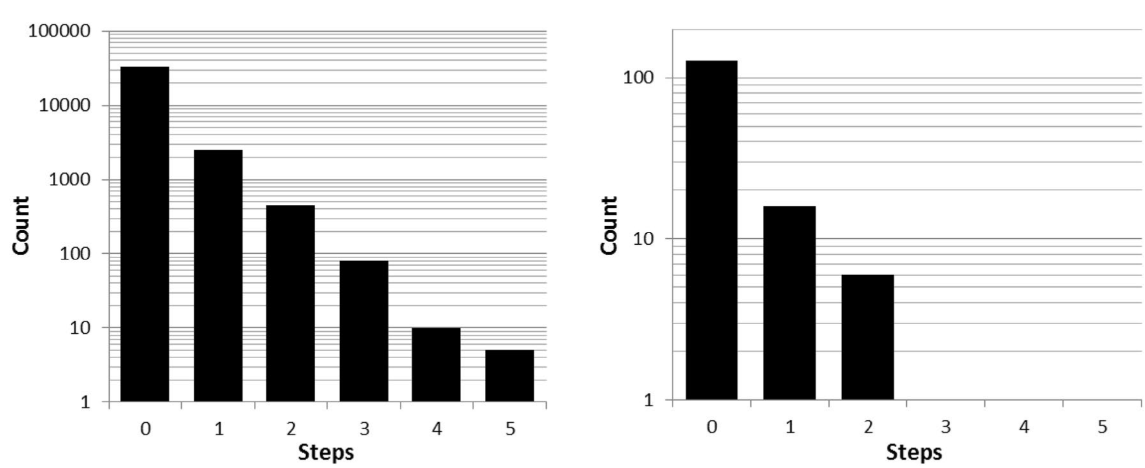

Fig. 15 Count of changes for every number of steps, for Pasqual and de Weck (2012) on the left, and the E-bike on the right (logarithmic scale). The '0' in the steps axis indicates the count of changes that did not originate in propagation

Table 9 Summary of case study vs existing work

Criteria	Observations	Similar?
Cr1. Documentation of change requests	Mature firms had a bureaucratic process; the E-bike did not have official forms or procedures	No
Cr2. Change resistance and cancelled changes	Resistance was frequent in the reviewed papers, while inexistent in the E-bike. The E-bike also showed less cancelled changes	No
Cr3. Changes evolution	The evolution in the reviewed papers followed a 'ripple' pattern, while the E-bike showed an 'avalanche' while getting closer to the race	No
Cr4. Propagation length	The reviewed papers showed relevant propagation until five-steps, while the E-bike rarely surpassed two-steps	No
Cr5. Changes distribution	Both contexts exhibited concentrations around few critical components	Yes

the immediate problem solving and was verbally based, with more flexibility but minimum idea recycling. An improvement in this context could be the development of technologies capable of registering verbal decisions and their arguments. This could aid young organisations that need flexibility, but also reusable knowledge.

5.2 Cr2. Change resistance and cancelled changes

There was less change resistance (almost none) and less cancelled changes in the E-bike (see Sect. 4.2 for a detailed analysis), which we believe was caused by the influence of third parties in each context. In mature firms, the third parties affected significantly the adoption and reflection of changes, while in the E-bike they were irrelevant. Young organisations should consider this variable and take precautions that allow them to maintain their independence to implement changes as needed.

5.3 Cr3. Changes evolution

The evolution of changes in the E-bike was similar to an 'avalanche', while mature firms were similar to 'ripples'. This 'avalanche' was probably caused by the later establishment of the requirement–component relations, which in mature firms was done from the start. This suggests that changes are less likely to propagate out of control if the relations between components and requirements are established as early as possible. Young organisations could benefit from this observation, avoiding reactive strategies that could end in dangerous avalanches (see Gelderen et al. 2000).

5.4 Cr4. Propagation length

In the E-bike, the propagation length was shorter than in mature firms because, such as in Cr2, the minimum involvement of third parties allowed to solve—or absorb—the changes without much propagation. This shows the benefits of blocking third parties and establishing relations between components and requirements as soon as possible (even one step). However, not all young organisations can avoid third parties or internal agendas, which could multiply the effect of "small" changes.

5.5 Cr5. Changes distribution

This was the only similar criterion between mature firms and the E-bike. Although we expected it (mostly because of Pareto principle), it was also reasonable to believe that in relatively simple systems all components could be equally relevant. Our results show that in a university design context, changes and its propagation are concentrated in a small number of components, and the same could be expected in other young organisations.

Consequently, we consider that it is not adequate to use ECP tools developed for mature firms in a university design context, neither young organisations in general. Table 9 presents a global view of the previous, including the most relevant observations when comparing the E-bike results with the observed in mature firms. As mentioned in Sect. 2.3, a robust statistical analysis remains a challenge since the existing work does not follow any standard.

6 Conclusions

Designing in young organisations can pose different challenges as compared to designing in mature firms. To determine if there is a need to develop specific support tools, it is necessary to understand how engineering change and its propagation can differ between these two design contexts. In this paper, we examined the evolution of change in a university design project—an electrical motorcycle modification—and compared the results with previous work done at mature firms. We found that in the university design context, 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 rechanges are likely to occur during the project when more is understood from the EC requirements. However, this does not necessarily result in more change propagation, as it was observed 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 the project could have prevented or prepared the design team for 67% of change propagation. When comparing the obtained results with those observed in mature firms, the university design project was less documented (Cr1), was not resistant to change (Cr2), concentrated its changes near the deadline (Cr3), propagated less (Cr4), and showed EC concentrations around a small number of components (Cr5).

We have interest in knowing if mature firms are in a better position to pursue incremental change as they have the option to build on their existing infrastructure, or the constraints arising from the same infrastructure has a bigger negative impact. The findings of this work suggest that mature firms are in a more complicated position when pursuing incremental changes and support the idea that designing in young organisations, such as university student teams, can pose different change challenges as compared to mature firms. Hence, the work suggests that ECP tools developed for mature firms can be unsuitable for young organisations. The findings also suggest that young organisations can benefit from using verbal systems to administrate changes, reducing the involvement of third parties, establishing requirement–component dependencies between as early as possible, and isolating the components that can propagate in depth.

Given that this work was conducted using a case study approach, we acknowledge that the results are limited to the context of our case study. We accept that new cases may deliver different results. However, it is necessary to start somewhere. We believe our criteria, results, and comparison with previous studies are the first of their kind, and we hope to see related research to be able to compare their findings with ours.

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