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UNDERSTANDING THE ENGINEERING DESIGN PROCESS THROUGH THE EVOLUTION OF ENGINEERING DIGITAL OBJECTS

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1. Introduction

The work performed within the engineering design process almost always produces a set of digital objects as a result, be it communication through tools such as E-Mail, or the generation of a product representation such as a Computer Aided Design file (CAD). Engineering projects typically generate thousands of these digital objects as they progress through the phases of the engineering design process. For example, McMahon et al. [2004] study on the search & retrieval of engineering records analysed a portion of a shared network drive that contained 38,500 files, Wasiaks' [2010] work an analysing the content of engineering E-Mail covered some 10,000 E-Mails from a single project and the dataset presented in this paper contains approximately 1,000 captured communications and 13,500 files. In addition, the increasingly distributed nature of large engineering projects is necessitating the wider use of digital objects to share knowledge & information, and therefore it is likely for the volume of digital objects to increase further. See for example, Figure 1, which shows Airbus' facilities across the world and includes 12 offices, 11 production sites, 12 design offices & engineering centre, 6 final assembly lines, 121 support centres, 7 material & logistic centres, and 21 training centres.

Figure 1. Airbus sites around the world (Source: http://www.airbus.com/worldwide/#)

It has been shown that the management of these digital objects within an engineering project utilises a large number of disparate systems [Gopsill et al. 2011] (Figure 2). The application of information systems has become an integral part to supporting engineering work as a means to overcome the traditional traceability and process bottlenecks inherent in paper-based documentation [Ives and Learmonth 1984], [Roy et al. 2004]. Argyres [1999] argues that the development of 'very-high' technological aircraft (such as the B-2 stealth bomber) would not be feasible without these information systems. And it has been shown that if properly implemented, information systems can increase the productivity of development teams [Dyer and Nobeoka 2000].

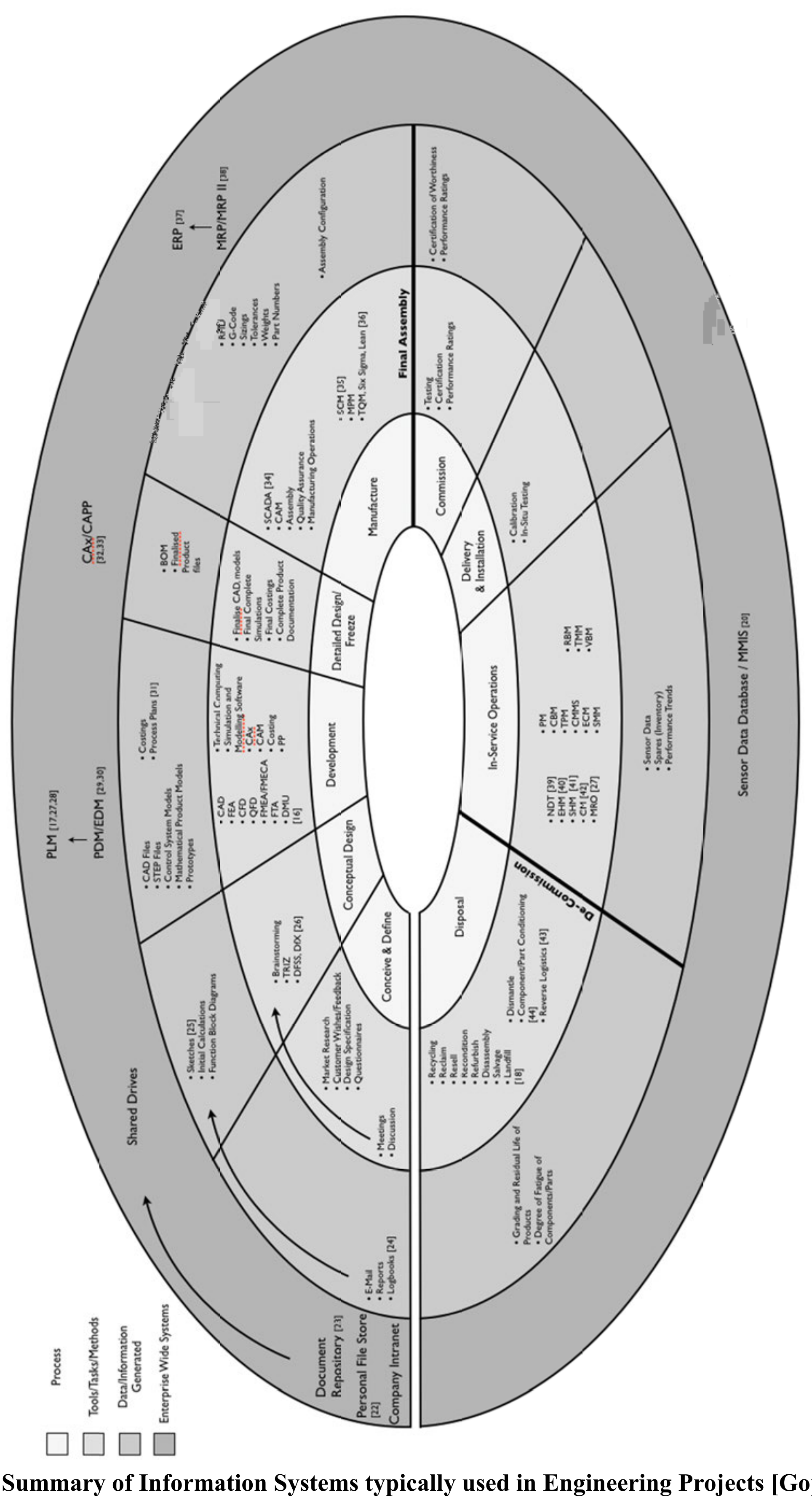


Figure 2. Summary of Information Systems typically used in Engineering Projects [Gopsill et al. 2011]

Although there has been research with respect to understanding the influence of information systems on engineering projects as well as the development of the information systems to support engineering projects (see for example Ming [2005] and Liu and Xu [2001]), little research has been performed on understanding how the evolution of digital objects could inform us of events occurring within the engineering design process. It is argued that these objects have been generated by engineers to support their work and that insights or patterns from the evolution of these objects could align to certain design process phases and/or emergent behaviour and thus become signatures that can provide a real-time indication of the state of an engineering project. Potential behaviours could be indicating divergent and convergent thinking, level of collaboration between teams and team/project cohesion.
To investigate this, this paper presents some initial findings from a exploratory study that has captured the generation of digital objects from a Formula Student engineering project. The paper focuses on whether patterns could be observed from the analysis of the meta-data of digital objects; if so, hypothesises on how they might relate to engineering project performance and the Formula Student project plan have been made.

2. Study context – Formula Student

"Our mission is to excite and encourage young people to take up a career in engineering. It seeks to challenge university students to conceive, design, build, cost, present and compete as a team with a small single-seat racing car in a series of static and dynamic competitions. The format of the event is such that it provides an ideal opportunity for the students to demonstrate and improve their capabilities to deliver a complex and integrated product in the demanding environment of a motorsport competition."
Formula Student Mission Statement (Source: http://www.formulastudent.com/formula-student/about-us)
Formula Student (FS) is an educational programme aimed at developing the next generation of race engineers through a motor-sport based project. Competitions are held across in the world (for example, in the UK, US[1] , Australia and Europe). Teams of students from their respective universities are placed in charge of designing, developing and manufacturing a single-seat race car that competes within the various challenges set-out by the competition (Figure 3). This is also a highly multi-disciplinary and collaborative environment involving the expertise of students undertaking various engineering courses such as automotive, aerospace, electrical, manufacturing and mechanical. The judging of the competition is not only based upon how the car performs at the event but also how the team can provide and deliver the rationale behind '*why the car they have designed is the way it is*'.

Figure 3. TBR13 Car

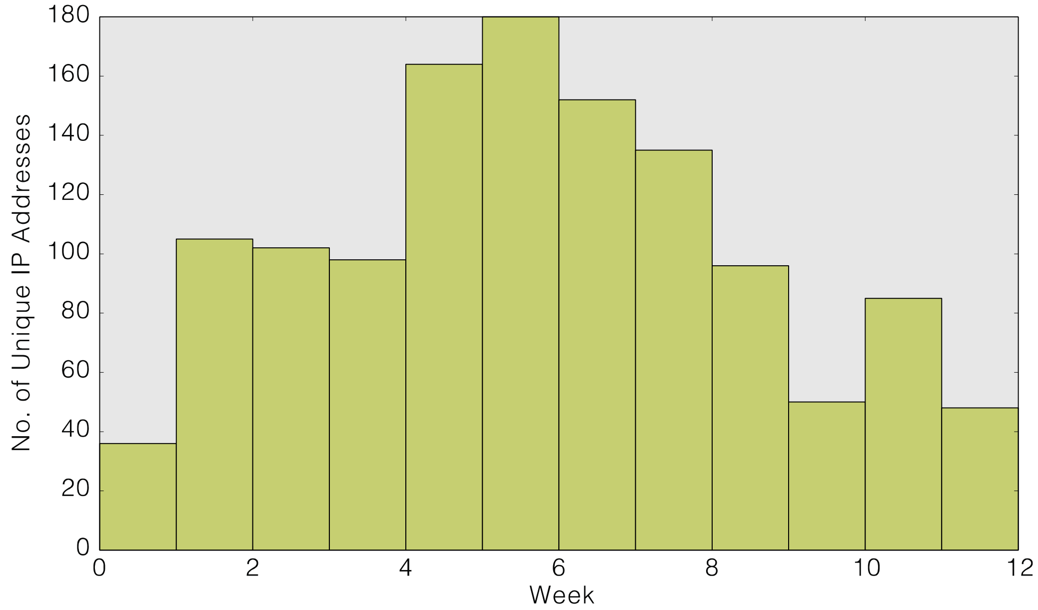
[1] Formula SAE

The 2013 Team Bath Racing (TBR) team is made up of 33 engineering students. The Formula Student project is primarily run at the University and in the case of the TBR team, there is an allocated workshop and shared file space for the storage of their digital objects. Therefore, it may be argued that the study is not one of a distributed team but of a collocated team. However, Figure 4 shows the main flows of network traffic accessing the shared file space over the period of the study and reveals that there must have been cases where some members of the team were working away from the allocated workshop.

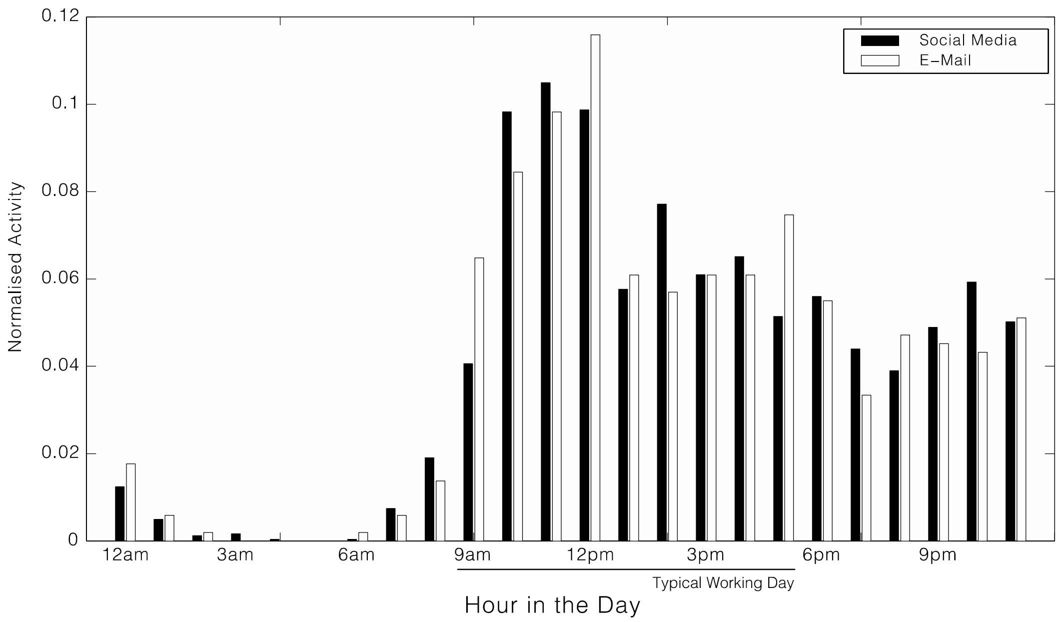
Figure 4. Network Traffic Accessing the Shared File Space

It is interesting to note the 30% of the traffic has come from the London area although one has to recognise that the traffic is passing through main network hubs and therefore this may be traffic for the South East region of the country. Although, this does provide evidence to show that the project has an element of geographically distributed working.

This is further confirmed by Figure 5a showing that there were a high number of unique IP addresses used throughout each week, which indicates access from multiple devices. Also, Figure 5b shows the ratio of communications occurring throughout the day and that in this study the computer-mediated communications continued passed the typical hours of a working day. Therefore, it is argued that the students continued to work at home during the evenings, which necessitated continued discussion. It is interesting to note that approximately 30% of the communication from the team occurred after 6pm. From this analysis of user activity, it is argued that the study is one of a distributed team.



(a) Number of unique IP addresses within each week that were used to communicate with one another



(b) Occurrences of Computer-Mediated Communication

Figure 5. Formula Student Communication Activity

3. The Study

The study took place across an eleven week period of the Formula Student project and involved the capturing of the communication digital objects throughout this period and the evolution of the digital objects being stored on the shared drive. Thus, two data capture strategies were required for each dataset.

With respect to the communication digital objects, the students used both E-Mail and Social Media. The students were requested to label each communication by its intended purpose. This was achieved by providing the students with a set of templates that automatically placed the purpose label within the subject header of the E-Mail. These are summarised in Table 1. The labels have come from previous studies involving engineering e-mail communications [Wasiak 2010], [Gopsill et al. 2013a] (http://www.raspberrypi.org), [Gopsill et al. 2013b]. A copy of each communication has been taken and stored from the project.

Table 1. Communication labels that the students could apply (from [Gopsill et al. 2013a], from [Gopsill et al. 2013b])

E-Mail Label	Description
Idea[1]	Wants to show something potentially new
Help[1]	Wants to solve a process problem
Issue[1]	Wants to solve a product problem
Clarification[1]	Wants to double-check their knowledge on a subject
Observation[1]	Wants to highlight an artefact of potential interest
Confirmation[1]	Wants to ensure the artefact is correct
Comparison[1]	Wants to converge on a solution
Option Generation[1]	Wants to generate a number of solutions
Information Request[1]	Wants to receive information or be provided with its location
Decision[1]	Wants to propose a decision
Project Management[2]	Roles of Responsibility, Deadlines, Meeting Planning & Task/Process Management
Customer Facing[2]	Quotations, Customer Support, Sales and After-Sales
Social[2]	Evening Plans, Talking with Friends and *'the football last night'*

In order to capture the evolution of the digital objects stored on the shared drive, a Raspberry Pi[2] was utilised to monitor the status of the network drive at 20-minute intervals. The generated script would check the folder/file structure alongside the timestamps (i.e. date changed) of the digital objects. Any changes would be recorded and stored in a MySQL database and a copy of the altered digital object taken and stored on a RAID hard drive. This enables the study to build up the evolution of each digital object stored on the shared drive over the eleven-week period.

The secondary data for the analysis is the project plan that has been generated by the team, which is summarised in Table 2.

Table 2. Formula Student Design Process

Stage/Milestone	Week
Conceptual Design Stage	Weeks 0-4
Design Freeze Milestone	Week 5
Detailed Design Stage	Weeks 5-11
Technical Report Hand-In	End of Week 8
Post Hand-In Review Team Meeting	Beginning of Week 9

4. Results

Table 3 provides a summary of the dataset that has been created. During the eleven-week period, an error occurred with the Raspberry Pi capture device, which led to two weeks of missed changes. This will be highlighted during the discussion of the results.

Table 3. Summary of the Dataset that has been created

Summary Information	Value
Total number of E-Mails	509
Total number of Social Media messages	2,441
Number of original E-Mail communications (i.e. no replies or forwards)	194
Number of original Social Media communications (i.e. no replies)	488
Number of distinct file names created on the shared drive	13,459
Number of changes to the files	29,650
Final shared file space size	100.58GB

[2] http://www.raspberrypi.org

4.1 Communication Digital Objects

Figure 6 shows how the various types of communication change as the team progressed through the engineering design process. Each of the areas represents the relative proportion of that particular type of communication for each of the eleven weeks. It can be seen that 'Project Management' communication is greater in the first few weeks and reduced as the project continued. A logical conclusion is that the team were taking the first few weeks to organise themselves and assign roles. 'Ideas' appear throughout the conceptual design phase and reduce once the project passes the *design freeze* and moves towards the *detailed design*. One could hypothesise that the divergence and convergence of idea communication may be related to how much of the solution space has been explored by the engineers. Moving to 'Information Request', it can be seen that the level remains relatively constant throughout the design process potentially indicating that it may be independent relative to the design process stage. However, 'decisions' appear to peak and trough at various stages of the design process. Many 'decisions' appear early on and again, this is likely due to the team organising themselves and assigning roles. They appear once again at the *design freeze* stage of the process as the team decide on the direction that they wish to take and then appear heavily at the *technical report hand-in* and *post hand-in meeting*. This hand-in is for the set of reports that are to be assessed by the judges at the competition and could be considered analogous to a stage-gate review. Therefore, the 'decisions' before could be related to what the team are going to present and the convergence of the solution and the decisions after could be due to the feedback from the review process. 'Clarification' communication slowly increases over time and appear more in the *detailed design* phase. These may be used by the engineers to maintain awareness of the decisions made on the design and ensure their work is aligned with others. Looking at 'issues', these appear heavily during the *conceptual design* phase and may go hand-in-hand with 'idea' communication. Traces of these two communication types could be considered to indicate the level of collaborative problem-solving occurring at a particular stage of the project. 'Issues' do appear after the review hand-in, which may indicate issues that were raised in the review process. Finally, 'confirmation' communication appears throughout the design process although heavily at the hand-in period. This seems a logical conclusion as the engineers are looking for more awareness of the project state and to approve and reaffirm their work with others before the hand-in.

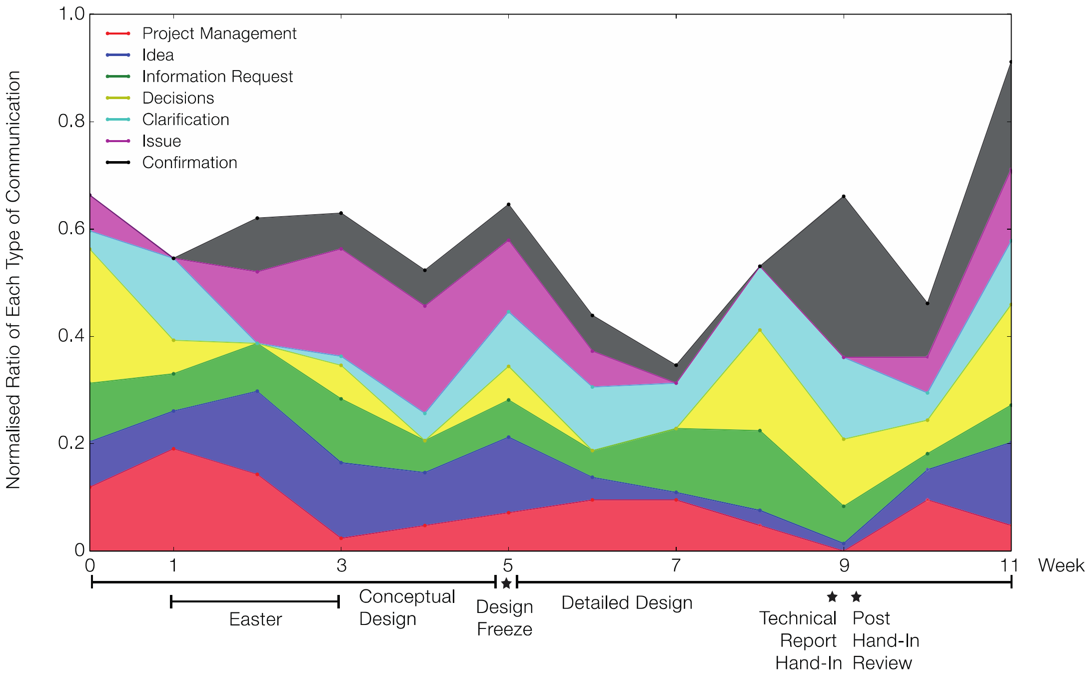


Figure 6. Types of communication throughout the engineering design process

4.2 Engineering Record Digital Objects

Figure 7 presents the file activity within the shared file space and in particular the creation, renaming and removal/movement of files. The key points to highlight are that there appears to be a correlation between the creation and the deletion/movement of files during the conceptual design phase. This may indicate that throughout this stage, the engineers are constantly adjusting and organising the file space as they are seeking potential solutions for the design for the Formula Student car. Also, hardly any files were either created or deleted during the Easter period, which provides an indication of the graph's validity as one does not expect much work to occur on the shared file space during this period. As the team progressed past the *design freeze*, the creation and renaming/removal/movement lines appear to diverge with the renaming/removal/movement line settling to a steady state. This indicates that the file structure that is to be used in the project has been finalised and that it is the case of generating files during engineering work and relating these to this structure. Therefore, the key point is that patterns can be observed between the creation and renaming/deletion/movement of files, which may indicate the level project cohesion. Finally, another aspect that validates the graph is the fact that the deletion/movement matches the creation of files. This is because all the files were moved to a new file space at the end of this study.

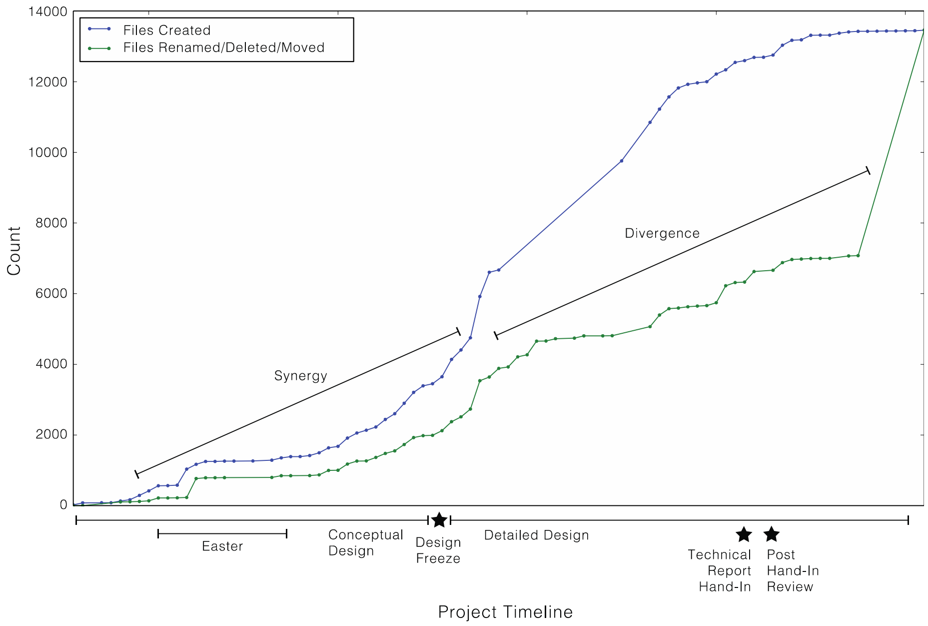


Figure 7. The Creation and Deletion/Movement of Files on the Shared File Space

Increasing in granularity, Figure 8 presents the normalised cumulative frequency of the creation of various types of digital objects during the project. It can be seen that images, spreadsheets, editable engineering documents, static engineering documents and CAD all appear from the outset of the design process, whilst CFD (WorkBench, CFD, CFD data Backup) appear later in the design process and actually greatly increase after the *design freeze*. This appears to make logical sense as CFD work often requires a lot of resources (in terms of engineer hours) and requires a defined form in order to build a mesh from. An interesting point is that the CFD backups appear between days 40-60 and these files are typically used as final results. Thus, it is likely at the end of this period was where the CFD results used in the *technical hand-in* was completed. The appearance of these documents along the timeline could provide indicators as to whether the work is occurring at the *right* stage of the project. The editable engineering documents can be seen to have a fairly steady rate of increase throughout the project whilst the static engineering documents see a step change just ahead of the *technical report hand-in*. This may highlight that the final technical design was finalised just ahead of the hand-in and again, this is a logical conclusion as the students rush to complete their work ahead of a deadline. However, in a real-world project this could be an indicator of rushed/hurried work that may not necessarily be complete.

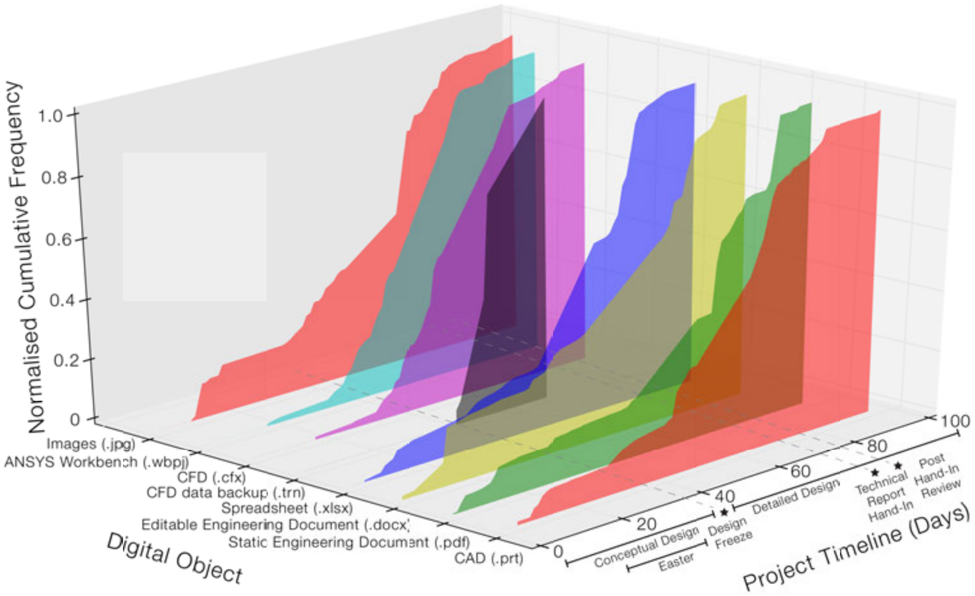


Figure 8. Types of Digital Object created during the Project

Taking a more in-depth look at the generation and changes of the CAD files where a total of 1637 were created and 8508 changes were captured, Figure 9 shows the evolution of a subset of these files during the Formula Student Project with four key areas being highlighted. Area (a) shows a significant step change in Engine Assembly, which may be indicative of a sudden rush of work and/or delayed start. From this step change, the Engine Assembly aligns with the Car Frame (b), which shows that these two files are clearly separated from the rest of the CAD files. This could be an indicator that these assemblies could be heavily affected by the rest of the design. (c) shows the cohesion in the evolution of the sub-assemblies of the product and it can be seen that both the rates in the evolution of (b) and (c) are similar, which may also indicate a level of cohesion with the design of the product. While only a single project is considered in this paper, it may be the case that the evolution of CAD files within engineering projects and a deviation may highlight potential events that needs to be addressed by the project management team. It can also be seen that many of these CAD files were being generated before the *design freeze*, which suggests that some aspects of the design had already been agreed by the team prior to the event. The final aspect (d) shows the issue with the data collection tool and thus, no data has been collected for this period.

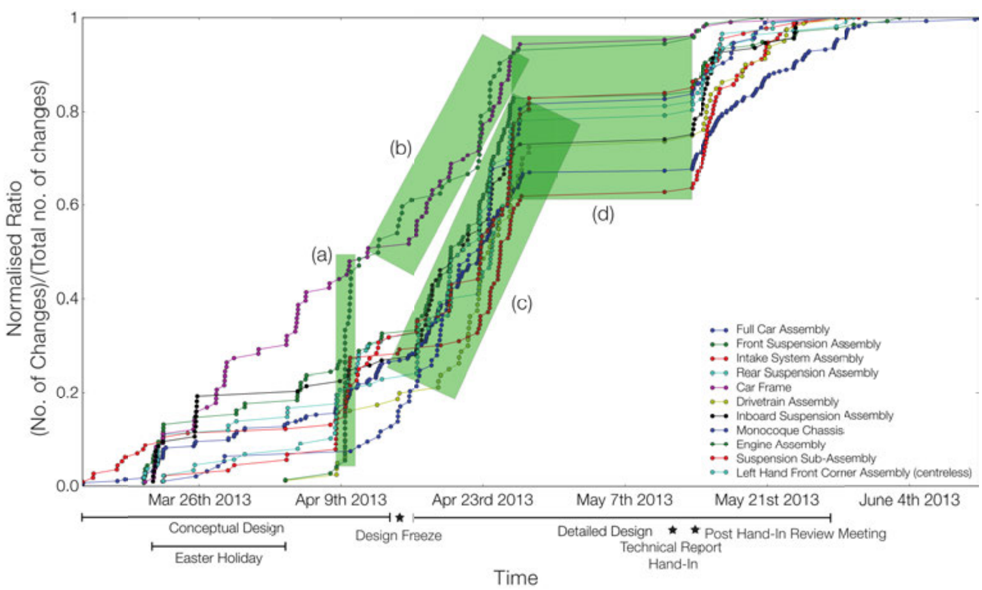


Figure 9. The Evolution of CAD files during the Project

Moving onto the final result but continuing on the analysis of the CAD files, Figure 10 shows matrix plots of when various types of CAD files relating to various aspects of the product were created and changed. The dotted boxes highlight the key interesting pattern, which appears across 5 of 9 aspects of the product. The pattern is that there are many changes made to existing CAD files two weeks prior to the generation of many new CAD files. At first, this may seem counter intuitive. However, it is argued that this the initial set of CAD files are generated as an iterative step of the design process and these changes are iterations of the design within the CAD environment. Once finalised, the engineers create new CAD files that become the final product files based on the iterations made in the initial files. Although only speculation at first, the pattern for this case is that one can expect the final iteration of the CAD files to be produced two weeks after a stage of much iteration. In addition, a synergy can be observed between Electrical System and Brake System files in both the files created and changed. Such patterns may indicate the level of interaction that has to occur between the sub-systems of the various disciplines.

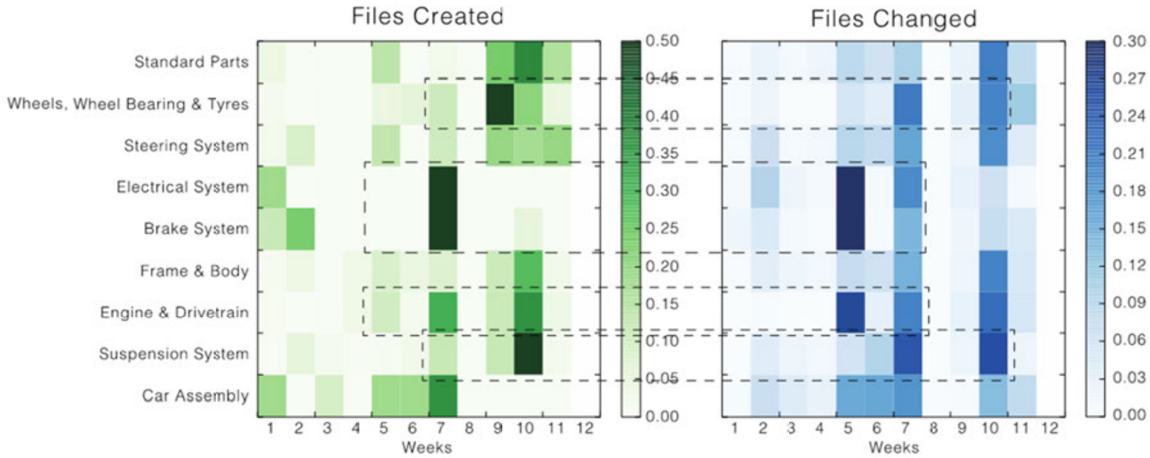


Figure 10. Matrix plots of the CAD file creation and changes made

5. Next Steps

The analysis of the meta-data has demonstrated that trends and potentially interesting patterns can be seen and that they could be related to the activities, phases, states and behaviour within the project. However, the full meaning behind the patterns cannot be ascertained and has led to hyoptheses and speculation. Therefore, the next step in this research is to seek to attach further meaning to these patterns, which would produce knowledge on the evolution of engineering projects. By achieving this, one could potentially monitor (in real-time) the *health* of an engineering project and also measure its performance. Examples include the ability to predict when is the most opportune moment to perform a design review, to monitor the convergent/divergent nature of engineering work and ensure it it occurring at the *right* stage-gates, and to produce project normality metrics for a given company that could be used to *steer* future projects.

6. Conclusion

This paper has discussed the increasing importance of digital objects in engineering projects with much research on the management and sharing of engineering data and information. However, it has been highlighted that there is a gap in whether there are identifiable patterns within the meta-data of the digital objects that could describe and/or support the engineering design process. Thus, this paper presents the results from an initial study to explore this question. From the analysis of types of communication digital objects and the evolution of digital objects stored on a shared file space, where patterns have been identified alongside a discussion to their potential relation to the design process. These patterns can be summarised as follows:

- The appearance of various purposes of communication could be indicative of the stage of the engineering design process, level of problem-solving and the reaching of key milestones.

- The synergy between files created and files renamed/moved/deleted could indicate the level of project cohesion.
- The creation of certain file types could indicate stages of the design process as well as their rate of creation potentially indicating hurried/rushed work.
- Several patterns in CAD file evolution could be observed, which could relate to design process stage, late/delayed work and/or interaction of sub-systems from various engineering disciplines.

In addition, the paper proposes the next steps in associating further meaning behind these meta-data patterns.

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