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COMPUTER AIDED DESIGN USER INTERACTION AS A SENSOR FOR MONITORING ENGINEERS AND THE ENGINEERING DESIGN PROCESS

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1. Introduction

In less than half a century Computer Aided Design (CAD) software has become a fundamental and integral tool in the design of almost all engineering products. Such is its prevalence and importance to engineering design that it is often taught as a dedicated module in engineering design curricula. Further, the CAD industry has recently been estimated to be worth $7 billion U.S. dollars with revenues being distributed 37%, 38%, 21% and 4% for the Americas, Europe, Middle East and Africa (EMEA), Asia and the Rest of the World (ROW) respectively, and as of 2011 there were an estimated 19 million users worldwide [Peddie 2012].

From its humble beginnings as a digital 2-dimensional drawing tool aimed at improving the accuracy and speed of engineering drawings [Sutherland 1964], CAD is now able to support the development and handling of complex 3-dimensional components and large assemblies comprising thousands of components. The utility of the software has also been greatly extended to include:

- automatic detection of interference;
- automatic generation of support documentation (such as the Bill-of-Materials) and standard parts;
- analysis of engineering systems; and
- support for concurrent and collaborative working.

In addition to the core geometric modelling capability of CAD, there is a wealth of software that either integrates into or complements CAD such as Finite Element Analysis, Dynamics Analysis, Computational Fluid Dynamics, and Product Data/Lifecycle Management systems.

For the reasons previously stated, it is generally accepted that the increased capability of CAD software has been a key enabler in the realisation of more complex products. This is in terms of handling the volume of parts, sub-assemblies and assemblies, the variety of interfaces between engineering systems and range of dependencies between features of the product. For example, the Boeing 787 Dreamliner consists of over 300,000 parts modelled in CAD and the Product Data Management (PDM) system commonly saw between 75,000 to 100,000 accesses a week during development [Briggs 2012].

It therefore follows that many engineers spend significant portions of their time interacting with CAD and their motives have become increasingly varied. An example of this variety is the need to perform an analysis and as a medium to support engineering communication [Robertson and Allen 1993]. The increased complexity of CAD software is also leading to engineering companies developing/requiring engineers with specialisms and expertise in particular areas of the software in order to maintain a competitive advantage and continue to develop innovative products.

One of the consequences of the prevalence, importance and increasingly specialised nature of CAD tool chains is that the quality, cost and timelines of the design process depends heavily on what can be thought of as the efficacy of user interaction with CAD. This includes how models are constructed, manipulated, edited, combined, re-used, modified and post-processed. One potential method of exploring this concept of efficacy of CAD users is to capture and examine the underlying log history generated during the use of CAD in a design project. In order to investigate the potential of such an approach, this paper examines the CAD activity from an undergraduate Mechanical Engineering course. The paper first discusses related work and recent approaches that directly or indirectly employ CAD as a sensor for monitoring engineers and the engineering design process. This is followed by an outline of the study and study context whereby the method of capturing 45 participants' CAD data, and a description of the pulley being modelled are discussed. Statistics of the dataset are then presented and results are examined to understand how differences in CAD logs manifest themselves. A discussion then ensues as to whether useful insights can be drawn from the analysis of CAD activity and it's potential as a sensor for monitoring the engineer and engineering design process. In addition, areas of future work are also discussed.

2. Computer Aided Design logs as a sensor

As CAD plays such a significant role in the design of engineering products, it comes as little surprise that researchers have already begun to investigate the potential of CAD interaction as a sensor for understanding engineers and the engineering design process. Both Liu et al. [2014] & Nguyen and Zeng [2014] have studied engineer physiology whilst performing CAD operations under scenarios of varying stress levels. Through the application of electroencephalography (EEG), galvanic skin resistance (GSR) and electrocardiography (ECG) techniques, the studies concluded that they were able to effectively monitor the stress levels of the engineers and indicated that the decisions made within the CAD system could be influenced by the stress level of the engineer. Although obtrusive in its nature (i.e. means of data capture and that the studies focused on the effect of stress on user behaviour), the positive correlations reveal the possibility to invert the process and thereby be able to use CAD logs as a potential indicator of the level of stress an engineer is under. Similarly, Diwarken and Jonson's [2012] study shows that the framing of an engineering task can significantly effect the time taken to complete the task and that while the final features of the CAD models remain consistent between the frames, the sequence of CAD commands differed. Again, this highlights the potential of CAD logs to provide insights into the tasks of engineers.

The aforementioned examples of stress level and task are not the only insights that could be elicited from CAD logs. Sung et al. [2010] show how engineering knowledge and design rationale could also be elicited. Their study demonstrated how the iterations of the users working with the BAMZOOKI zoo-kit editor were able to be logged and mapped to IDEF0 and Design Rationale Editor (DRed) knowledge representation models, and in doing so, greatly supported the collaborative design effort as well as enhancing traceability of design decisions.

Further, Nguyen et al. 2012 has sought to understand the potential of bioinformatics to generate useful information from the log files. Even though it has shown great potential in eliciting sub-sequences of potential import, there remains a wealth of techniques that could complement and/or provide additional insights such as the techniques used in web log mining, sequence analysis and/or eye tracking [Bakerman and Gottman 1997], [Agosti et al. 2011], [Mooney et al. 2013], [Boa et al. 2015].

While capturing and processing CAD logs appears, on initial inspection, to be straightforward, there are a number of complications that need to be considered. In particular, the volume of commands captured and length of sequence requires methods and approaches that can group commands in a more meaningful way. This is in addition to determining the most appropriate alignment of commands to the well-established types of engineering activity [Sim and Duffy 2003]. As it may be the case that insights into some of the engineering activities cannot be inferred from CAD logs (such as the Design Management Activities) whilst others could be inferred at a higher level of granularity (such as Design Definition Activities).

Although concise, this review highlights the potential for insights to be generated with respect to engineers' activity and engineering design process. However, challenges remain in terms of the volume of commands being captured and the ability to aggregate across commands and identify features that provide useful information on the engineer and engineering design process. This paper now continues by describing the study and the associated context, where the aim has been to understand how differences in CAD logs manifest themselves.

3. Study context and statistics

The study has captured the CAD activity of a 2nd year CAD course using AutoDesk Inventor. The students are tasked with designing a range of components that eventually leads to the generation of a car wheel and suspension assembly. The aim of this study has been to investigate how differences in CAD log files manifest themselves and given the context, the focus has been on ascertaining competency and detecting whether a student is having difficulties with the exercise.

Therefore, for the purpose of this study, the pulley component has been selected as it is the first component they model on the course (Figure 1). For many students, this will be the first time that they will have used CAD and thus, the level of experience will be consistent (i.e. Novice). For those who have used CAD previously, the differential in experience will be most significant during the construction of the first component. In addition, as students progress through the tutorials, the rate at which they complete the tasks varies and this presents additional challenges in capturing and organising the logs with respect to the components being modelled. A final consideration is that the pulley design represents the most constrained task provided on the course as the students all complete the same pulley design (Figure 2). Thus, it is argued that this provides the best opportunity for being able to detect variations within the user interaction and the construction, manipulation and editing processes of the students.

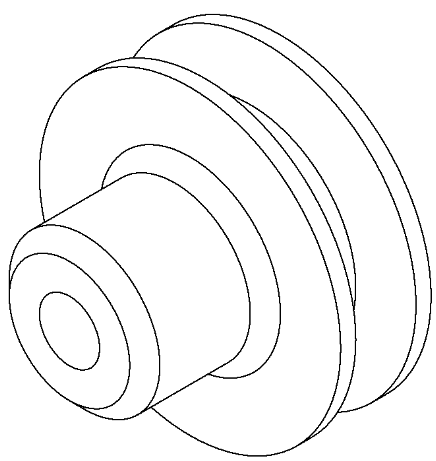


Figure 1. Pulley modelled by the 2nd year students

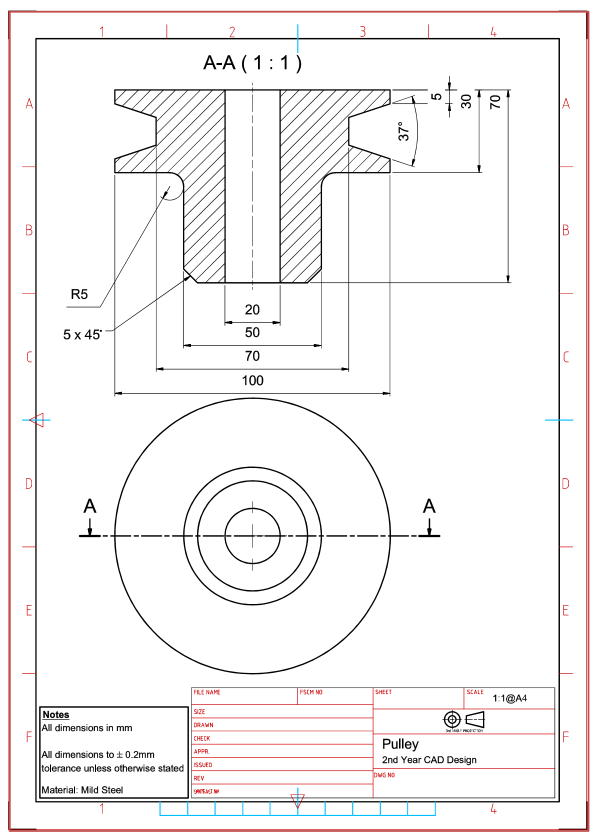


Figure2. Design drawing of the CAD pulley

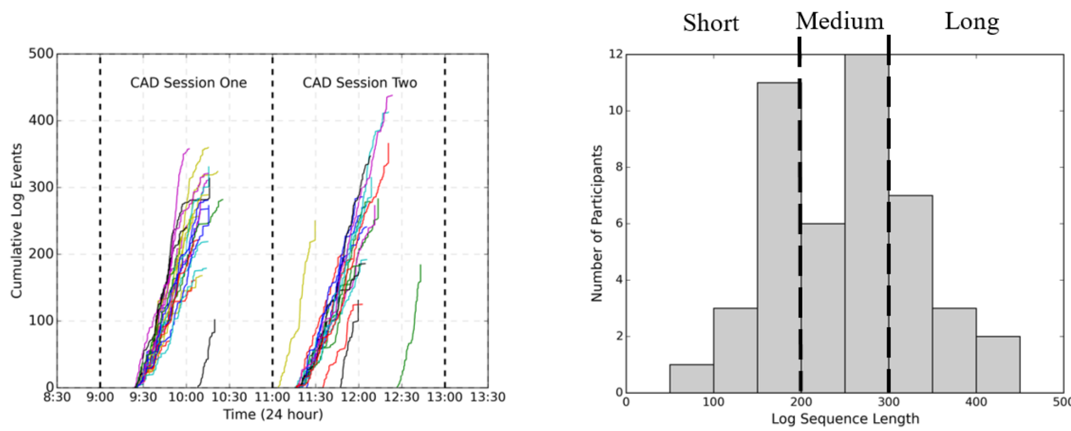
In total, 45 students participated, which resulted in a dataset containing 164 unique commands with a combined appearance of 88,450. In order to reduce the size of the log sequences and remove potential noise introduced by commands that are computer generated, rather than user generated, the commands were categorised in relation to geometry and command types of potential interest (Table 1). The categorisation enables exploration of the time students spend working in a 2D (i.e. sketch) and 3D (i.e. extrusions, cut-outs, chamfers and fillets) geometric spaces. In addition, categorisation of command types afford the ability to map onto the established design activity types as summarised by Sim and Duffy [2003]. In this case the events have been defined as creating, constraining, editing, deleting, reversing and viewing.

Table 1. Categories used in the analysis of the CAD log files

	Geometry	
Command Type	**2D**	**3D**
Creating	PartNewSketchCmd SketchCenterPointCircleCmd SketchLineCmd SketchProjectGeometryCmd SketchTwoPointRectangleCmd SketchTrimCmd SketchProjectCutEdgesCmd SketchMoveCmd SketchTwoPointCenRectangleCmd SketchPolygonCmd SketchOffsetCmd SketchExtendCmd SketchRotateCmd SketchMirrorCmd SketchHoleCenterPointCmd	ModelingEvents.OnNewParameter PartDMExtrudeCmd PartDMRevolveCmd PartDMChamferCmd PartDMFilletCmd PartDMHoleCmd PartNewSketch3DCmd PartDMShellCmd
Editing	SketchEditSketchCtxCmd AppDimensionEditCmd	PartNGxExtrudeEditCtxCmd PartNGxRevolveEditCtxCmd PartNGxFilletEditCtxCmd PartNGxChamferEditCtxCmd
Constraining	SketchHorizontalConstraintCmd SketchVerticalConstraintCmd PartWorkPlaneCmd SketchEqualConstraintCmd SketchFixConstraintCmd SketchParallelConstraintCmd SketchSymmetricConstraintCmd SketchGeneralDimensionCmd SketchAutoDimensionCmd	
Deleting	TransactionEvents.OnDelete ModelingEvents.OnDelete AppDeleteCmd SketchEvents.OnDelete	
Reversing	TransactionEvents.OnAbort TransactionEvents.OnRedo	
Viewing	AppLookAtCmd SketchSliceGraphicsCmd AppFreeRotateViewCmd AppPanViewCmd AppGroundPlaneToggleCmd AppZoomCmd AppZoomWindowCmd SketchShowAllGeometricConstraintsCmd SketchShowAllConstraintsCmd AppZoomSelectCmd	

The CAD logs were recorded during two CAD sessions that were two hours each and the accumulation of commands over time for each CAD log is displayed in Figure 2 part a. It can be seen that the majority of the CAD logs commence thirty minutes into their respective sessions and this is due to the lecturer presenting the outline of the course and providing a demo of the pulley within the first half-hour. Part b of Figure 2 shows the distribution of the CAD logs in relation to the length of their sequence. At first, it appears that the distribution is bimodal although this may be an artefact of the number of participants and bin size. In order to analyse the dataset further, the CAD logs have been grouped into three categories, which are defined as:

1. short (<200 events, and covers 15 CAD logs);
2. medium (200 < no. of events < 300, and covers 18 CAD logs); and,
3. long (>300 events, and covers 12 CAD logs).



(a) Cumulative frequency of commands from the CAD logs

(b) Distribution of log sequence length

Figure 2. General statistics of the recorded CAD logs

For the purpose of the analysis, thresholds have been selected so that the groupings have an equal number of CAD logs. The objective of their analysis is to ascertain how differences in the CAD logs manifest themselves. In order to do so, three features of the CAD logs have been investigated and include:

1. use of command;
2. proportion of command types; and,
3. transitions between commands.

These are considered with respect to the three categories of sequence (short, medium and long) to ascertain what makes a CAD sequence long when developing the same component.

4. Results

This section presents the results with respect to establishing what features contribute to making a sequence short, medium or long.

4.1 Commands use in CAD

Figure 3 and 4 reveal insights into the command use across the CAD logs as a whole and with respect to short, medium and long sequences. Figure 3 shows the number of participants utilising the various commands captured against the overall number of times they appeared within the logs. It can be seen that there exist three different groupings of commands independent of command type. These are: (i) commands that are used rarely by participants and may indicate CAD functionality that is not essential for the generation of the pulley model; (ii) commands that are used by half the participants and on a more regular basis and may indicate functionality used by participants who have approached the modelling in a different manner to the other half of the group performing the exercise; and, (iii) commands that are heavily used by all the participants and thus, are likely to be integral to constructing the model of a particular component. In addition to the groupings, the legend the indicates categories that each command belongs to. It can be seen that the most widely and heavily used command is one of 'deleting' followed by 'creating 3D', and then 'reversing'. As this is the first time that many of the students have interacted with CAD, this appears to be logical as many of the students will be selecting functions to discover their functionality and build-up an understanding of the CAD design process. The commands that contribute to the other command types such as 'creating 2d', 'viewing' and 'constraining' are distributed across the three groups (c.f. Figure 3). Although, it does appear that a combination of commands from the various command types are necessary for the formation of the pulley and indicates that even for a relatively simple design, engineers need to use all the command types in order to construct a model.

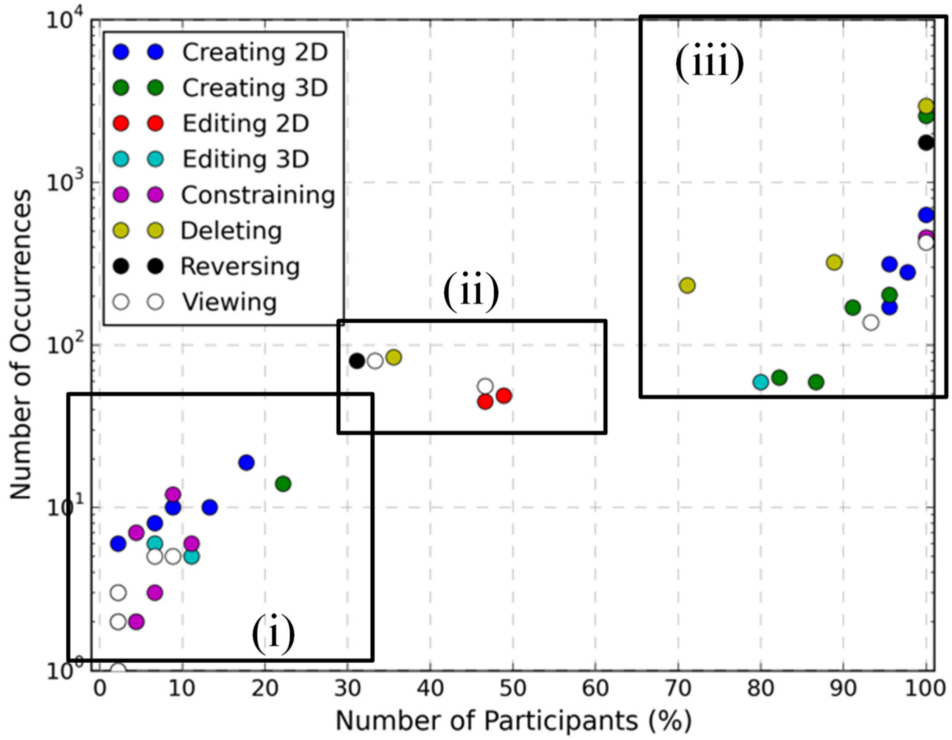


Figure 3. Use of CAD events across the three lengths of sequence

Figure 4 provides an additional perspective on the spread of command use and reveals how the commands are used in respect to the three lengths of CAD sequence. It can be seen that there are a set of commands that are applied by all students across all the groups and can be deemed necessary functions in generating the pulley model. There then appears a range of commands that occur in the medium and long sequences such as SketchOffsetCmd, SketchProjectCutEdgesCmd and SketchMirrorCmd. The small number of occurrences and the fact that they only appear within the medium to long sequences suggest that these are not necessary for the design of the pulley and that the appearance of these within a sequence may highlight a user with less experience and far less understanding of the tool. The final observation to note is the command set that appears in all lengths of sequence regardless of how heavily they have been applied. These include SketchEditSketchCtxCmd and PartNGxExtrudeEditCtxCmd. These commands feature in the 'editing' event type and thus, it suggests that the participants with longer sequences are spending more time editing the geometry they have created and indicates that they may be less precise when initially drawing the component geometry.

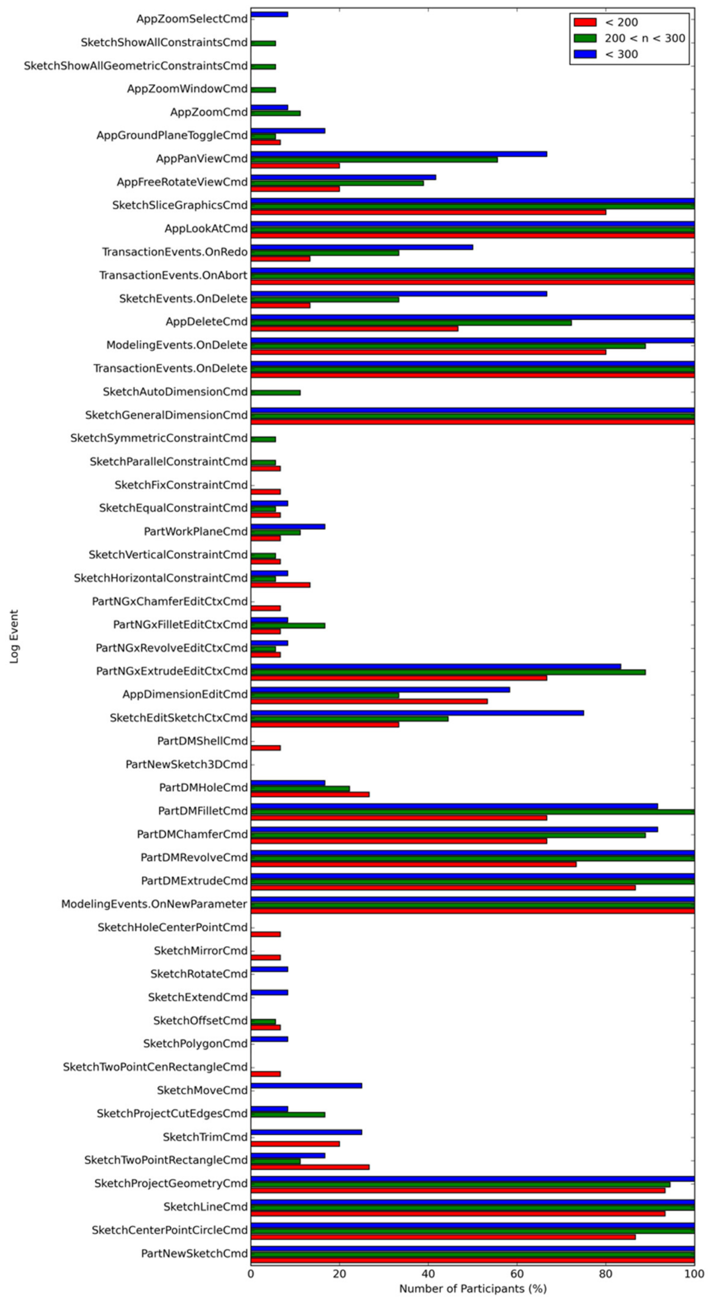
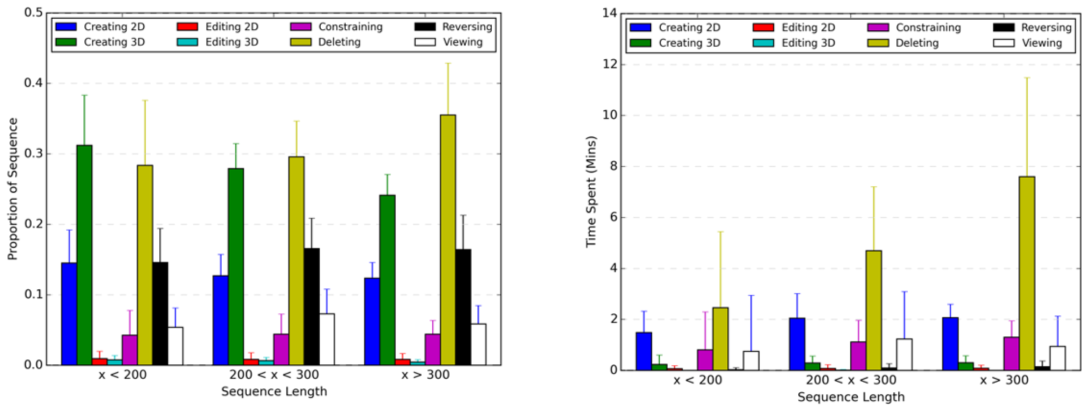


Figure 4. Use of CAD commands across the three lengths of sequence

4.2 Proportion of command types

Consistent with the previous analysis, the proportions of the command types has been grouped by the lengths of the sequences and the results are shown in Figure 5 part a. Each line represents the mean proportion of command use. The first aspect to note is the relative consistency for the majority of command types across the sequences especially for the 'editing 2D', 'editing 3D' and 'constraining'. However, 'viewing' appears to increase for medium length sequences and then decreases for long sequences. Thus, a characteristic trait of sequences increasing in length are that the participants spend more time manipulating the view of the model. The largest change in the proportions observed in the 'deleting' and 'creating 3D' commands. It can be seen that there is a substantial increase in 'deleting' and decrease in 'creating 3D'. Thus, it demonstrates that the long sequences are produced by participants who appear to have difficulty with creating and editing the geometry and prefer to use 'deleting' and 'reversing' in order to manipulate the model. This could also indicate that these participants are having difficulties in applying appropriate constraints to a model, which are necessary to facilitate ease of future editing.

Part a of Figure 5 also includes the error bars of the standard deviation for the command types and it can be seen that there is much greater variation in the use of the higher proportioned command types such as 'deleting' and 'creating 3D'. This highlights that although the model is of a relatively simple design, the sequence and path the participants take can vary considerably.



(a) Proportion of sequence by command type **(b) Time spent by command type**

Figure 5. Changes in the proportions of command types based on sequence size

In comparison, part b of Figure 5 shows the time spent on each of the command types. The first feature to highlight is the significant increase in time spent on 'deleting' whilst the majority of the commands remain of a similar proportion of time. Thus, this is the main contributor to overall time taken to complete the task. In addition, it is important to note that although 'creating 3D' took up a higher proportion of the sequence 6a) the actual time spent creating 3D geometry and also, the time spent on creating 2D geometry is considerably more. This highlights the challenge in relating the appearance of commands with the design activity that the user is performing. Similarly, it appears that the time spent 'viewing' is also independent of sequence length with participants with longer sequences spending the same time selecting 'view' commands as those with shorter sequences.

4.3 Command transitions

To further investigate the use of command types and how they may influence one another, this section presents the analysis of the transitions between command types. Figure 6 provides an example of the transitions made between command types for each of the three lengths of sequence. Part a of Figure 6 shows an example of a small sequence for the generation of the pulley. It can be seen that there is a cycle of 'creating 2D' geometry followed by 'creating 3D', which was sometimes accompanied by a reverse command (c.f. (i) in Figure 6 Part a). After this, a period of deletion commenced (c.f. (ii) in Figure 6 Part a), which was then followed by the final generation of 2d and 3d geometry (c.f. (iii) in Figure 6 Part a). This could be interpreted as the user becoming familiar with the tools required, deleting any past geometry and then following up by creating the final geometry given their increased understanding of the tool.

Figure 6b shows the process for a medium length sequence and as in the shorter sequence, there is is a cycle of 'creating 2D' geometry followed by 'creating 3D', which was sometimes accompanied by a reverse command (c.f. (i) in Figure 6 Part b). Again, this is followed by a period of deletion, however, rather than the generation of the final geometry, the participant executes a series of geometry generation and deletion cycles (c.f. (ii) in Figure 6 Part b). This indicates a participant potentially having difficulties in interpreting the pulley design and translating the drawing into a 3D model (c.f. (iii) in Figure 6 Part b).

Part c of Figure 6 presents the results for the longer sequences and appears to follow a similar pattern to the medium sequence length, however, the cycle of geometry creation and deletion appears a lot more severe (c.f. (ii) in Figure 6 Part c). Also, in contrast to the sequences of medium length where participants go back a few steps in the process and re-do them, participants of longer sequences appear to delete the entire set of geometry and start again. This may highlight difficulties the participant may be having in either: generating geometry that is constrained, editable and re-useable; interpreting the 2D drawing provided and creating a 3D model; and/or, an element of frustration in completing the exercise.

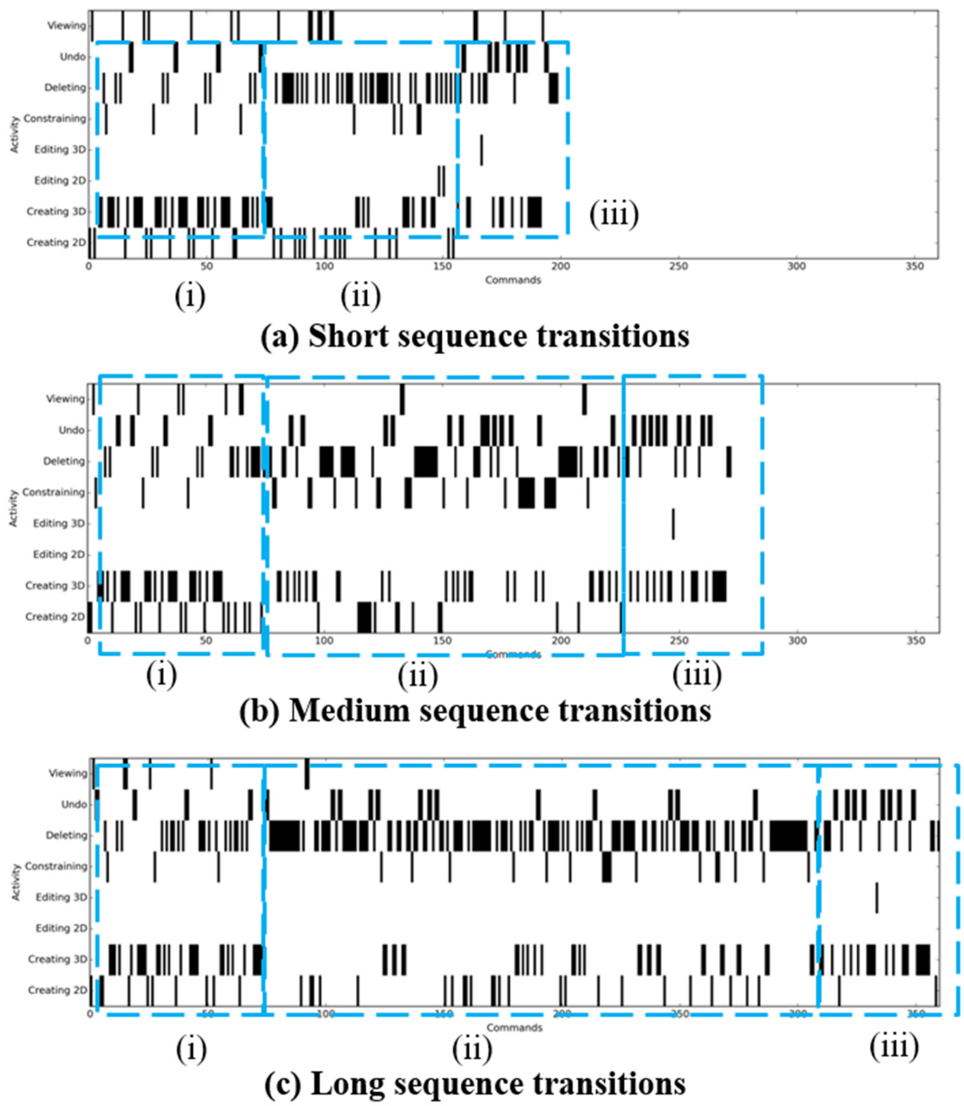
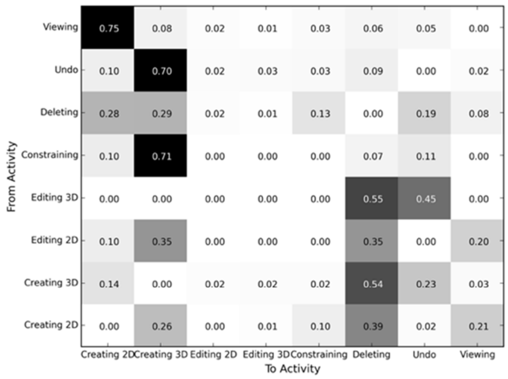


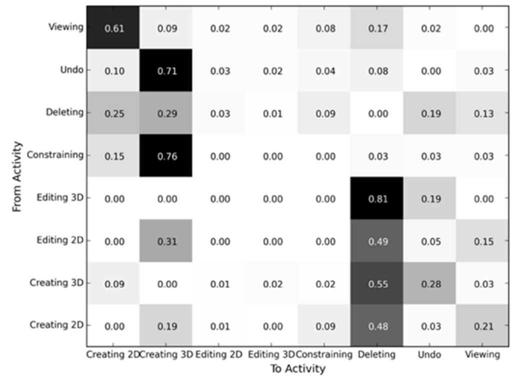
Figure 6. Transition sequences from the small, medium and long sequence lengths

To investigate the aforementioned observation further, Figure 7 presents the results from the transitions matrices for the three sequence groups. These have been generated from the aggregation of the sequences within each group. Figure 7 shows the potential coupling of the event types within the different sequence lengths. Part a of Figure 7 shows that for small sequences, 'viewing' is frequently followed by the generation of 2d geometry, whilst reversing is followed by creating 3d geometry. This appears consistent throughout all the sequences. In addition, the range of transitions from one event to another is greater in shorter sequences. This highlights that the participants are more comfortable in moving between the various command types. However, this is not so for the medium and longer sequences where the transition pathways become a lot more defined. In particular, 'Editing 3D', 'Editing

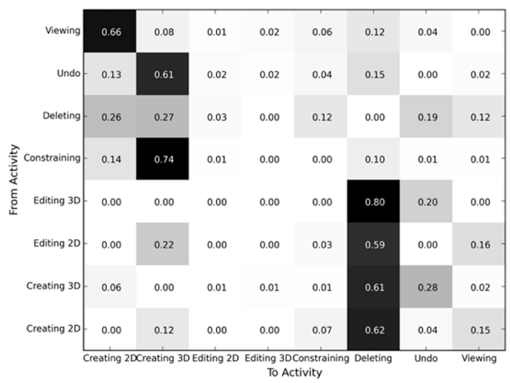
2D', 'Creating 3D' and 'Creating 2D' are increasingly followed by 'Deleting'. This suggests that for longer sequences, participants are having difficulties in both generating the geometry and the ability to constrain it appropriately so that it can be edited without causing issues with the model.



(a) Small sequences



(b) Medium sequences



(c) Long sequences

Figure 7. Transition matrices between the event types captured within the CAD logs

5. Discussion and future work

This exploratory study has provided some initial insights into the potential of CAD logs to provide insights into the activities of engineers and the engineering design process, and how differences between sequences manifest themselves. In terms of the use of commands within CAD logs for the design of the pulley, it was revealed that there were three groups of commands. These are:

1. core commands used that are independent of the component being modelled and/or necessary for the development of the specific component;
2. commands used by a small group of participants who have approached the modelling of the component in a different manner; and,
3. commands used by very few people that are most likely irrelevant or unnecessary to the component being modelled.

Given these findings, there is potential for future work to develop signatures for various components in terms of the commands required and this could be used to monitor progression, the competency of an engineer creating the component and as a method of identifying the type of component being produced. Moving to the proportions and time spent on the command types, 'deleting' has been identified as the main contributing factor to the sequence length and time spent on modelling the component. The level of 'deleting' could be used as a monitor to highlight a particularly challenging component to model and/or where further support is required by the engineer. In addition, the importance of taking a 'sequence' and 'time spent' view has been shown through the prevalence of 'creating 3D' in terms of the number of commands selected whilst ‘creating 2D’ has more time spent on it. This poses an interesting area for future work in understanding the affordances of sequence and time spent analyses.

The last aspect considered event transitions where it was shown that the small, medium and long sequences all follow a similar macro pattern of creation, deletion and creation of the final component. However, the micro patterns reveal that medium and long sequences showed increased iteration through ‘deletion’ and ‘reversing’ with the longer sequences highlighting a consistent deletion of the entire geometry before remaking the component rather than editing existing geometry. This has been further confirmed by the transition matrices. These initial results have demonstrated the potential of using transitions to understand engineers’ interaction and modelling approach within the CAD environment. In the case of this study, the transition matrices identified the challenges the participants were having with the generation of constrained geometry that could be easily edited as it was seen that participants with longer sequences reverted to deletion and re-making rather than editing. Future work in analysing transitions could identify further user interaction behaviour which could then be to support the monitoring of engineering projects.

In addition, this study has only focused on a single component being modelled by participants with little to no knowledge of CAD software. The authors are continuing their research into more complex CAD models including assemblies, and also investigating the user interaction of participants with varying levels of experience.

6. Conclusion

Computer Aided Design (CAD) plays a fundamental and pivotal role in almost all engineering design activities and supports the generation of the primary digital embodiment of the product. With engineers increasingly spending more time using CAD, CAD logs have the potential to provide a non-obtrusive sensor for the monitoring, assessment and evaluation of engineers and the engineering design process. This paper has evaluated this potential with an exploratory study of 45 participants generating a single CAD component with the aim of understanding how differences within the CAD sequences may manifest themselves. Analysis of CAD logs revealed three groupings commands of commands, which are: core commands used that are independent of the component being modelled and/or necessary for the development of the specific component; commands used by a small group of participants who have approached the modelling of the component in a different manner; and, commands used by very few people that are most likely irrelevant or unnecessary to the component being modelled. In addition, deletion and time spent creating 2D geometry were the primary factors in increasing sequence length and time spent generating the model. This has been further supported by the transition matrices highlighting that participants with longer sequences preferred to delete geometry and re-make rather than edit existing geometry. This highlighted the difficulties these participants were having on generating constrained geometry that could be easily edited in the future and could use

References

Agosti, M., Crivellari, F., Di Nunzio, G. M., "Web log analysis: a review of a decade of studies about information acquisition, inspection and interpretation of user interaction", Data Mining Knowledge Discovery, Vol.24, 2011, pp. 663–696, doi: 10.1007/s10618-011-0228-8.

Bakeman, R., Gottman, J. M., "Observing Interaction – An Introduction to Sequential Analysis", Cambridge University Press, 1997.

Boa, D., Hicks, B. J., "Reviewing peer review, an eye tracking experiement of review behaviour", International Conference on Engineering Deisgn (ICED15), 2015.

Briggs, D., "Establish digital product development (DPD) Low End Viewer (LEV) and archival standard for 787 project", Collaboration & Interoperability Congress (CIC), 2012.

Jamali, H. R., Nicholas, D., Huntington, P., "The use and users of scholarly e-journals: a review of log analysis studies", Aslib proceedings: New Information Perspectives, Vol.57, No.6, 2005, pp. 554–571.

John Peddie Research, "Jon Peddie Research releases the Worldwide CAD Market Report 2012", 2012, Available at <http://jonpeddie.com/press-releases/details/worldwide-cad-market-report-2012/>.

Liu, Y., Ritchie, J. M., Lim, T., Kosmadoudi, Z., Sivanathan, A., Sung, R. C. W, "A fuzzy psycho-physiological approach to enable the understanding of an engineer's affect status during CAD activities", Computer-Aided Design, Vol.54, No.0, 2014, pp. 19–38, ISSN 0010-4485, doi: http://dx.doi.org/10.1016/j.cad.2013.10.007.

Mooney, C. H., Roddick, J. F., "Sequential Pattern Mining – Approaches and Algorithms", ACM Comput. Surv. 45, 2 Article 19 (February 2013), doi: 10.1145/2431211.2431218

Nguyen, P. T., Steinart, M., Corroll, A., Leifer, L., "Applying bioinformatics analysis principles to cad data to better characterise and understand the design process", In DESIGN 2012, 2012.

Nguyen, T. A., Zeng, Y., "A physiological study of relationship between designer's mental e↵ort and mental stress during conceptual design", Computer-Aided Design, Vol.54, No.0, 2014, pp. 3–18, ISSN 0010-4485.

Prasad Diwakaran, R., Johnson, M. D., "Analyzing the effect of alternative goals and model attributes on CAD model creation and alteration", Computer Aided Design, Vol.44, No.4, 2012, pp. 343–353, ISSN 0010-4485.

Robertson, D., Allen, T. J., "CAD system use and engineering performance", IEEE Transactions on Engineering Management, Vol.40, No.3, 1993, pp. 274–282.

Sim, S. K., Duffy, A. H. B., "Towards an ontology of generic engineering deisgn activities", Research in Engineering Design, Vol.14, 2003, pp. 200–223, doi: 10.1007/s00163-003-0037-1

Sung, R., Ritchie, J. M., Rea, H. J., Corney, J., "Automated design knowledge capture and representation in single-user CAD environments", Journal of Engineering Design, 2010, Vol.22, No.7, pp. 487–503.

Sutherland, I. E., "Sketch pad a man-machine graphical communication system", In Proceedings of the SHARE Design Automation Workshop, DAC '64, pages 6.329–6.346, New York, NY, USA, 1964. ACM.

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