Investigating and Characterising Variability in CAD Modelling and its Potential Impact on Editability: An Exploratory Study

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Abstract. This paper introduces the concept of usability in the context of CAD modelling and editing, in particular, what is referred to as editability. Considering CAD models as a product, which often need to be reused, it is important to generate CAD models that are more usable in order to reduce editing time and errors and thereby accelerate product development. Analysing CAD construction process (a form of CAD modelling) as logged in [11] it was possible to characterise the variability in CAD models, their building process and consequentially, their editability. These findings and in particular, the observed variability in CAD modelling suggest that through improved training, guidance and best practice, it is possible to improve the editability of CAD models, potentially reducing future editing times, cost, and enabling easier transitions between engineers.

Keywords: Editability, Usability, CAD, Design Intent, Product Data Reuse
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1 INTRODUCTION

The 19th century signalled the beginning of modern technical drawing practice with the advent of Computer-Aided Design (CAD) [8]. Drawings were increasingly necessary to effectively communicate the rising complexity of parts and assemblies. Over time, new methods were researched to deal with the description of objects to aid the design prior to manufacture and construction [14]. These methods have evolved from 2D drafting tools to modern CAD and Building Information Modelling (BIM) systems. Commercial examples include, AutoCAD and Inventor, Fusion360, CATIA, and Solidworks [16]. Today's design processes, almost without exception, use some form of computer-based models, where digital models enable designers to easily introduce, exchange and collaborate on models as part of the design workflow. Computer-based models allow continuous improvement and refinement of the product, often preserving part and assembly constraints and associations, and enabling the reuse of existing parts [30]. [33] highlights that "reusing the design and manufacturing process from an existing design improves product development efficiency".

Such is the perceived ease-of-use and accessibility of digital models, CAD and simulation can now be performed by a wide range of users from novice to expert and from many different disciplines. While valuable for the design process in terms of innovation and quality of the final design, the variety of users and backgrounds results in variability in CAD model structures by virtue of the varying practices, objectives and mental models [10]. It is the potential for, and presence of, this variability that this paper examines. A concept that has seen relatively little in the field of CAD [22].

Engineers and product designers with a high level of training are now required in order to maintain a competitive advantage over other companies. With increased skills coupled with increased software capabilities, CAD modelling software offers many ways of creating a visually equivalent 3D geometric model. This variability does not only impact the model, but also the engineering team as it influences the ability to collaborate seamlessly coming up with new products at a faster pace. One of the key means to achieve this is to reuse, modify or iterate existing CAD models [30]. Given this, it is logical to assert that if a model is more usable then reuse or iteration is easier and faster. The concept of Usability has been adopted in many fields [12, 25] and is used in this paper as a performance measure. It follows that the contribution of this paper is framed with respect to usability and examining if and how, models embody some sort of variability and how this might impact on usability.

The possibility of the existence of more Usable CAD models raises two long-term questions: Can such CAD models be identified and characterised? And can usability be quantified in the context of CAD models? Moreover, is one model more usable than another? Answering these questions does bring a substantial contribution to answering some of the 10 CAD challenges of our century [8], and this paper sets out to examine the presence of variability and explore its potential impact on usability – a key step to addressing some of these challenges. In order to achieve this, the paper first develops the concept of usability within the context of CAD models. Following this, a study of 12 CAD users is presented in order to examine variability in the modelling process and the structure of the model itself. Based on the results and the aforementioned concept of usability, the types and levels of variation are characterised and the potential impact(s) of process and model variability on usability are considered.

The papers explores evidence of variability in CAD models created by different users for the same object. Given the aforementioned variation in practice, objectives and mental models combined with the many variables (different CAD features and software commands) which designers can manipulate in the realisation of a CAD model of a known object, it is expected that both the CAD modelling process and CAD model itself will manifest some level of variability. In the context of CAD models, this variability will include the type and order of modelling processes, the geometric features and the model's level of specificity/specification. These, in turn, will likely impact the ability to use and/or reuse the model later in the design process.

The existence of variability in the CAD modelling process and its potential impact on the design process is implicitly acknowledged by CAD vendors, such as Autodesk. They offer training and guidance in interface commands, industry best practices, and other advanced skills so as to improve the speed and ease of building and reuse – Autodesk holds an Authorized Academic Partners (AAP) certification [4].

2 USABILITY AND EDITABILITY OF CAD MODELS

Nielsen [24] discusses in-depth the concept of usability and its testing methods and strategies in a large number of contexts. Considering the usability of a product or a system, it is possible to make some general considerations. These will require more specific concepts to be adapted to CAD models.

Table 1: Usability definitions

	Definition	*Ref.*
Usability	How a system/product/service be used by specified users to achieve the desired goals with effectiveness, efficiency and satisfaction in a specified context of use.	[5, 17]
Efficiency	The relation between (1) accuracy and completeness with which users achieve specific goals and (2) the resources expended in achieving them.	[19, 20]
User Satisfaction	Users comfort with and positive attitudes towards the use of the system.	[6, 24]
Effectiveness	The measure of accuracy and completeness with which user achieve certain goals	[19, 20]

2.1 Usability

Over time the definition of usability (Table 1) has been generalised because of its increased importance in product design and engineering design [23, 24, 25, 26]. Initially, its rise was attributed to the marketing importance of usability, making a product more appealing. Over time, the importance of inclusive design increased the scope of usability studies [24]. Nielsen [24] raises some further considerations regarding usability. Looking at the aforementioned definitions in Table 1, it is worth noting that, in the context of product design, the CAD modelling software also be viewed as either the product, the system or the service and an appraisal of usability undertaken. This paper is concerned with the CAD model itself and consequently the CAD modelling software is not considered.

Parameters of usability have been discussed in different fields of literature, and considerations made in [19, 20] lead to the conclusion that components of usability can be broken down in to three different contributors: effectiveness, efficiency and satisfaction [6, 7].

2.1.1 CAD usability

Considering the definition of usability for a specific product in Table 1, such as CAD models, it is possible to identify three important contributors [5, 17]:

- the user: the individual using the CAD model.
- the goal: the thing the user aims to achieve.
- the context of use: the situation in which the use take place.

In the introduction the authors focus on the fact that CAD models are a tool in the engineering design workflow, and at the same time point out the issues of use/reuse as highlighted in [8, 29]. The authors consider drafters of different levels of ability as users. The specific desired goal considered is how CAD models can be reused in design workflow. Finally, the context of use can vary from educational to industrial purposes as long as CAD models are reopened for reuse purposes:

- view: visualise the model to deduce information.
- interrogate: extract information from the model.
- modify: change properties of the model.

The specific usability is thus determined by the Design Intent of the user, which also affects higher lever aspects of usability of CAD models.

> *Def: **Design Intent**: Encapsulates sufficient knowledge of the manner in which the designer generated the model to permit it to be modified by the original constructional procedure [18, 31].*

Features are the primary building block of CAD models, and intrinsically their type and organization has a greater influence on the usability of the CAD model. The understanding of where features are located, and how CAD/CAM models were built, had more importance initially from a manufacturing point of view. Design intent and structure of a CAD model, have some level of influence on the usability of the model.

2.1.2 Arguments against measuring User Satisfaction

Effectiveness and Efficiency focus on user performance, which is the more quantifiable aspect of usability. By targeting performance, products/systems can be affected in multiple ways. In the context of CAD models, this affects the level of consumption of resources to achieve the same goal [6, 27].

Frøkjær [9] discusses the importance in isolating the contributor to usability for measurement. In the CAD modelling context, while efficiency and efficacy are determined by the model, satisfaction is considered to be mostly affected by the software environment.

2.2 Editability

Given this and Nielsen's description of usability, the term editability is used herein to reflect aspects of effectiveness, efficiency and satisfaction when using/reusing CAD models. Editability has been chosen as a sub measure of usability as it only takes effectiveness and efficiency into consideration.

> *Def: **CAD Model Editability**: The extent to which a CAD model can be edited in order to be used/reused in the design workflow by users with effectiveness, efficiency.*

3 VARIABILITY IN CAD MODELS AND CAD MODELLING

This section explores the existence of variability in CAD models and CAD modelling, which would confirm the potential for variability in editability also. The latter property can be explored if and only if there is variability. Data provided was recorded in 2015 by a research study using a logger [11]. Data from this study is used because the methodology employed controls both software and training-related sources of variability, allowing an exploration of user-related sources of variability.

One of the primary drivers for industry is reducing costs and increasing revenue, and this is often achieved by improving efficiency/productivity, as variability affects the time an engineer takes to familiarise themselves with a model. Considering the CAD models developed by drafters as a product, it is possible to start classifying the types of variability that could be measured.

It is possible to differentiate between:

- Product Variability: CAD Model Variability – (Output in Fig. 1).
- Process Variability: Modelling Process Variability – (Input in Fig. 1).

Fig. 1 indicates how CAD Model variability can be assessed by inspecting the final product either manually, or automating the process using an Application Programme Interface (API).

Control over sources of variability, such as industry-standards [15], exist in CAD models, but it is vital to take the parameters that influence these into consideration. Fig. 1 shows a list of quantifiable measures of

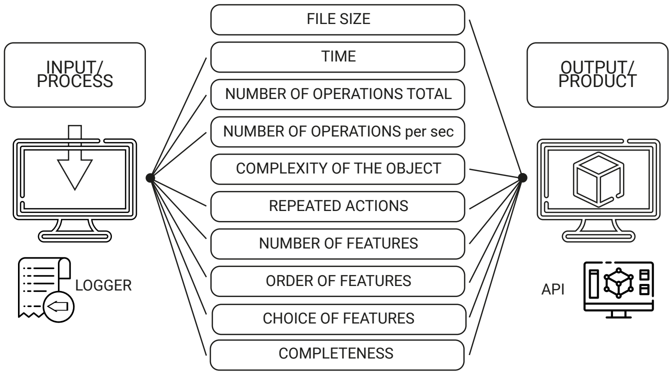


Figure 1: Sources of Variability in CAD models

variability in a CAD model alongside CAD modelling variability and associated measures Fig. 1. Measures of variability in CAD Models and the CAD modelling process are:

File size which might want to be minimised for different reasons ranging from displaying and navigating large assemblies to storage purposes.

Modelling time Total amount of time taken in building or editing a model. In general, the longer time correlates with greater number and complexity of operations performed to construct the model.

Total operations (Log length) The higher the number of operations the greater the potential for variability. Log length is measured as the number of *event*triggered throughout the process.

Operations per second (Modelling rate) Higher rates lead to more efficient modelling, but sometimes they can also lead to mistakes. Mistakes will be identified as *deleting* and *reversing events* in the experiment. This measure is expresses as the number of *event*triggered per second.

Complexity Complex features are harder to maintain in the long run and to edit, this can be solved by using simple editing commands and breaking down complex structures into smaller features.

Features (Number) An excessive number of features makes editing difficult. An over-compensated structure to a small number of features is harder to edit: this leads to higher effort (cognitive and physical) for feature recognition and extraction [28].

Features (Order) The structure and organisation of features in a CAD model can impact the ease of editing and the inter-dependencies created throughout the design process.

Features (Types) Often guided by industrial procedures which aim to increase editability, reduce downstream errors/issues, and enhance the use of a model for modelling and manufacturing purposes [15].

Completeness This measure affects the usability of a model, as an incomplete model cannot be used in future workflow. The level of completeness of a model can be attributed to the usability of the starting model.

The paper will focus on modelling time and rate, as the data collection focused on the modelling process.

4 METHODOLOGY

4.1 Approach, Method and Technique

In order to investigate the variability in the modelling process it is necessary to distinguish between different levels/perspectives associated with CAD modelling. The three perspectives include:

> *Def: **Approach**: how practitioners orient themselves towards aspects of their work.*

The highest level of characterisation is the approach taken in solving the problem. The decision to use a specific software instead of using other prototyping techniques for product development is the approach chosen for the task. In this experiment, the approach was predefined in order to control variables that could affect editability other than in-tool choices (c.f. Fig. 2).

> *Def: **Method**: the organisational patterns or practice protocol used both to set forth and bring forth aspects of the approach. The method encompasses how the approach both organises the activities of the systemic practitioner and facilitate the enactment of the approach.*

The transition between *event*, type of *event* and consequentially type and order of features highlight variability in the Method.

> *Def: **Technique**: the specific activities practised by users of the approach that can be observed and even "counted" by an observer of the activity.*

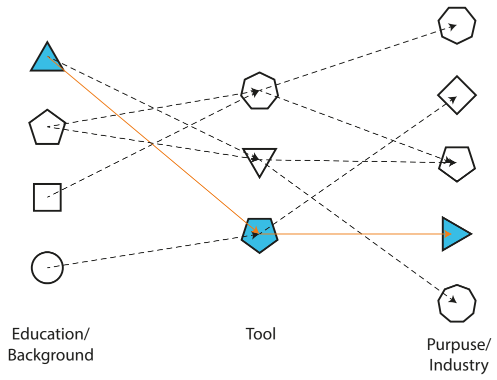


Figure 2: Sources of Variability in Product Design

Variability in technique can be established by comparing the difference in time and number of *event* that users devoted to, for example, observation compared to creation and editing. Another indicator of the difference in approach by the user is the rate of triggered *event*.

Approach, method and technique are influenced by user education/background, the tool used, and the purpose or the context in which CAD models are created and edited. These contributors are highlighted in Fig. 2 and further discussed in the following sections, as they are important variables to be controlled.

4.2 CAD Modelling Study

Fig. 3 outlines the experiment and how the data was analysed. In the experiment design phase Gopsill created a logger used in [11] and drawings were generated from the parts. Then a group of 12 users were recruited across a University's Department of Engineering. They were given information on an assembly and its parts

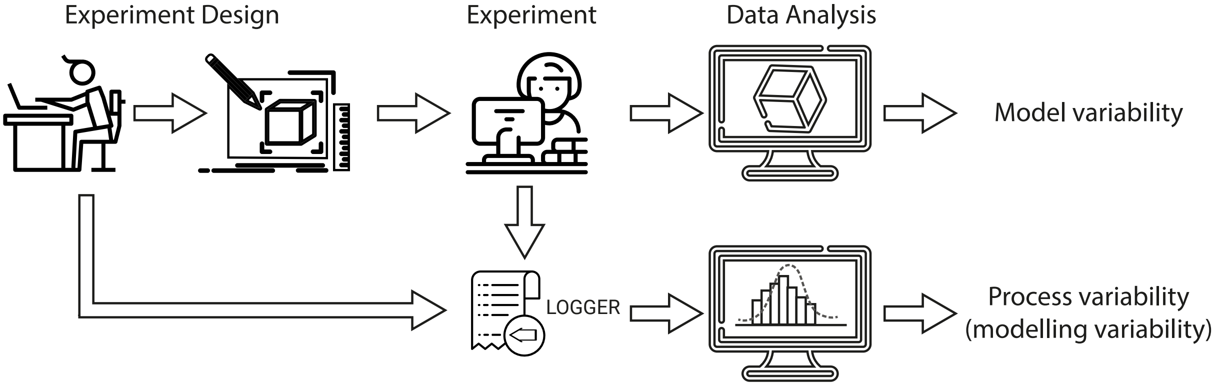


Figure 3: Experiment

(Fig. 4), that were required to be modelled in Autodesk Inventor. A reward was offered as an incentive to work efficiently, rewarding the correct models that were constructed in the least amount of time. Beyond collecting all the files of completed parts and assembly, it was possible to log every *event* taking place in Autodesk Inventor during this study. Submitted files were analysed to investigate model variability, while the logger data revealed tendencies of users informing on modelling variability. The choice in using engineering students as users in this study is supported by [1, 2, 3], as the measured design processes can be related to those of professional engineers.

[6, 9, 12, 23, 24, 25, 26] outline different methods to assess the usability of a system/product. As the reported methods are consistent with the approach employed [11] it can be asserted that the Data recorded is valid for studying usability concerned with measures of performance and observation. While these measures do not allow us to understand in depth the interdependence between variables causing variability, they confirm its existence.

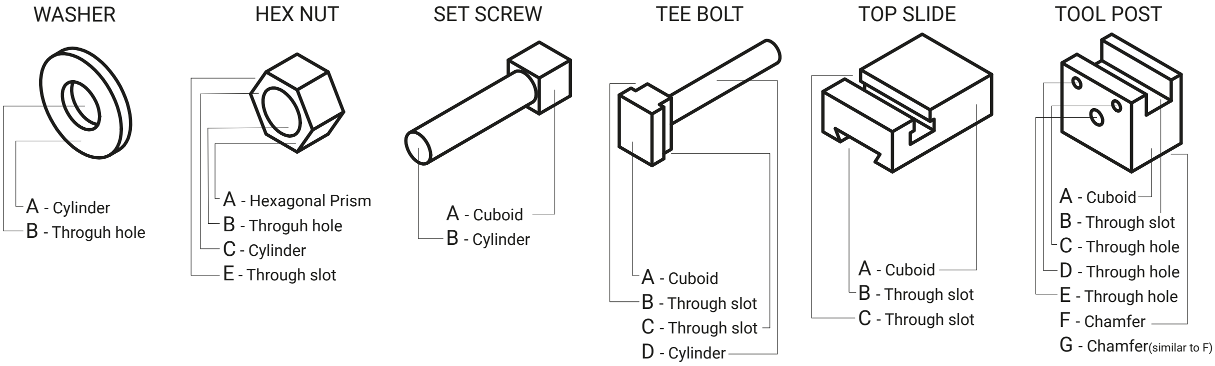


Figure 4: Features in Object Assigned to users.

An extract of the raw data as recorded by the logger is shown in Fig. 5. The data was parsed using Python into a Pandas Data Frame [21] which isolated each command, details regarding it, the time it took place, the user that carried out the event, and file on which the *event*took place. The logger also records*events*which happen in the background, thus it is necessary to isolate specific types of commands recorded.

```
15/12/2015␣10:17:47
ApplicationEvents.OnNewDocument
15/12/2015␣10:17:47
ApplicationEvents.OnNewView
15/12/2015␣10:17:50
ApplicationEvents.OnInitializeDocument
15/12/2015␣10:17:50
UserInterfaceEvents.OnEnvironmentChange
Display␣Name:Inventor
15/12/2015␣10:17:51
UserInterfaceEvents.OnEnvironmentChange
Display␣Name:Inventor
15/12/2015␣10:17:56
ApplicationEvents.OnActivateView
15/12/2015␣10:17:57
UserInterfaceEvents.OnEnvironmentChange
Display␣Name:Assembly
```

Figure 5: Extract from Logger Raw data

4.3 Data Collection Procedure - Measurable Variables

During and following the experiment, data gathered and included: all the inventor files created by the users, a data logger designed and discussed in [11] to record all Autodesk Inventor commands used by the users. As discussed in Section 4.1 variability in the design process can be primarily attributed to three classes: background, method/tools and purpose (Fig. 2). Throughout this experiment, users that took part in the experiment were the same age; had a similar background in CAD design and possessed similar levels of education. The experiment was carried out on Autodesk Inventor, the same software the users were trained on. They had no previous knowledge of the task, and they were given the same information necessary to carry out the task – a detailed drawing of each part was provided – an example description of parts and features is given in Fig. 4. Under such conditions, the primary sources of variability outlined in Fig. 2 were controlled, leaving as a possible source the choices made by the users. It is important to note that certain industries are beginning to restrict such sources of variability by developing and imposing a set of instructions and rules provided to the engineers (good practice/standard procedures) [15].

4.4 Evaluating Model Variability

Because of the size of the population analysed (12 users), it was possible to analyse CAD Models by inspection. Following the order presented in Fig. 1, the variability in CAD modelling was explored at different levels starting from a macro level, and drilling down in greater detail using Nielsen's usability inspection methods [26]. Model variability is explored starting from the CAD model size, which is the first property that can be measured, to the number and organisation of features within the CAD model. The rest of the properties analysed is Fig. 1 top to bottom.

4.5 Evaluating Modelling Process Variability

Possible modelling process variability can be inferred from the variability in CAD model structure. As highlighted in Fig. 1 it is necessary to use logged data (collected during the 'modelling phase'), and the related sources of variability. The analysis is carried out considering the time and the number of *events* used in building CAD models. Then the analysis delves into greater detail looking at the type of commands and how these relate to the speed with which users completed the tasks. Finally, processes are compared looking at their transition plots and transition matrices.

4.6 Evaluating Variability in CAD Model Editability

Inspection methods are used to identify variability in edibility. Given the available information about the CAD models considered the two main usability evaluations:

- Consistency inspection [26], which looks for inconsistencies across a set of interface designs. In the reported study, the CAD model can inspection be regarded as an interface for visualising and editing solid models.
- Feature inspection [24, 32], consists in listing sequences of "features used to accomplish a task". Given our context the "features" to which Nielsen and Wixon et al. Construction trees are list of sequence of features that can be used to evaluate whether design steps were too long, or too complex (which sometimes is the result of the attempt of being to short). This evaluation requires knowledge of the process which it aims to evaluate.

Given the use of the word 'feature' in the CAD context, it is important to highlight that the usability inspection methods called 'feature inspection' do not evaluate features, but sequences of *events* of a user operating with the interface. For this reason it might be easier to refer to it as *event* inspection within this context.

5 RESULTS

The experiment described in the previous section and in Fig. 3, produced CAD models and a data set from which it was possible to investigate the existence of variability in CAD models, their building process, and ultimately their editability.

Table 2: Construction trees

User	washer	hex_nut	set_screw	top_slide	tee_bolt	tool_post
01	Ab	Ab	B,A	Ab,c	Abc,D	Ab,fg,cd,e
02	Ab	D,e6	A,B	A,b,c	A,bc,D	A,b,cde
03	Ab	Ab	A,B	A,B,c	Abc,D	A,b,cd,tc,td,e
04	Ab	Ab	A,B	Ac,b	Abc,D	Ab,c,d,2d
05	Ab	Ab	A,B	Ac,b	Abc,D	Ab,e,cd
06	Ab	A,b	A,B	Ac,b	Abc,D	Ab,he,hcd
07	Ab	A,b	B,A	Ac,b	Abc,D	A,b,cde,e
08	Ab	A,b	A,B	Ac,b	A,bc,D	A,b,cde
09	Ab	A,b	A,B	Ab,c	Abc,D	Ab,cd,e
10	Ab	Ab	A,B	Ac,b	Abc,D	A,b,cd,e
11	Ab	Ab	A,B	Ac,b	Abc,D	Ab,e,cd
12	Ab	Ab	A,B,B'	Ac,b	Abc,D	Ab,cd,e

5.1 CAD Model Variability

File size, feature count, and contextualised *events*(types rather than edits and aborts) were some of the sources of variability listed in Fig. 1. For this part of the analysis it was enough to analyse the completed files (the output).

Overall, Fig. 6 highlights the first evidence of observable variability: the spread in size for files is greater for files with a higher number of features, perhaps because of the greater number of features, or the use of more complicated *modelling events*. The average size of each part appears to increase with the complexity of the

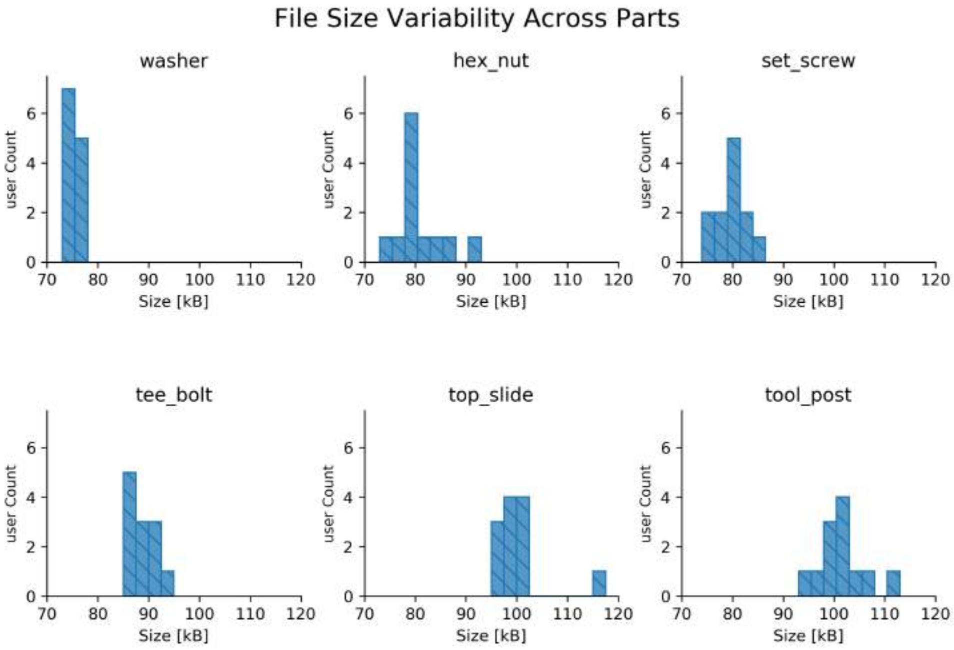


Figure 6: Variability in file size for part files

part as shown in Fig. 7, however, the complexity of the parts does not seem to impact the spread of the data. The file size is determined by the model construction process and the number of features used. Such variability raises a question about what factors cause it, and to what extent they contribute to the variability of models? In the circumstances where usability prioritises file size, it would make sense to explore the factors affecting file size variability in more depth.

CAD operations were counted and listed using notation indicated in Fig. 4, detailed results in Table 2. In Fig. 8 there is a count of single feature instances across all the parts. Fig. 8 shows a count of the permutations of features across the parts. Fig. 8 uses letters to refer to different features within a part. A legend giving meaning to each letter is shown in Fig. 4: capital letters denote additive operations and lower-case letters denote subtractive operations. The *comma* is used to delimit the different features identified in the construction tree.

Fig. 8 shows variability in the choice of features, in nearly all parts. The only parts that are expected to exhibit a similar final construction tree are: the washer and the nut. Unexpectedly, the *hex_nut* shows a more extensive variability in the choice of features. Despite having the same topology as a *washer*, the slightly higher complexity in the plan view might have caused the discrepancy in variability.

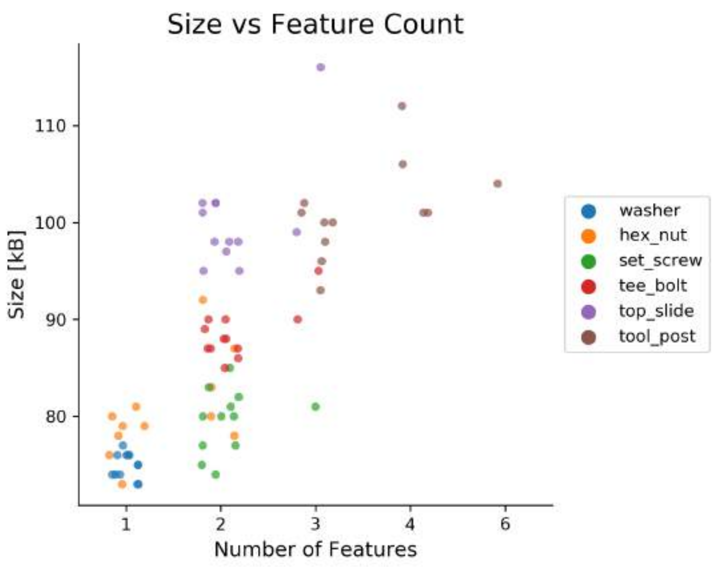


Figure 7: Variability in file size for part files against the number of features (proxy for complexity of a part).

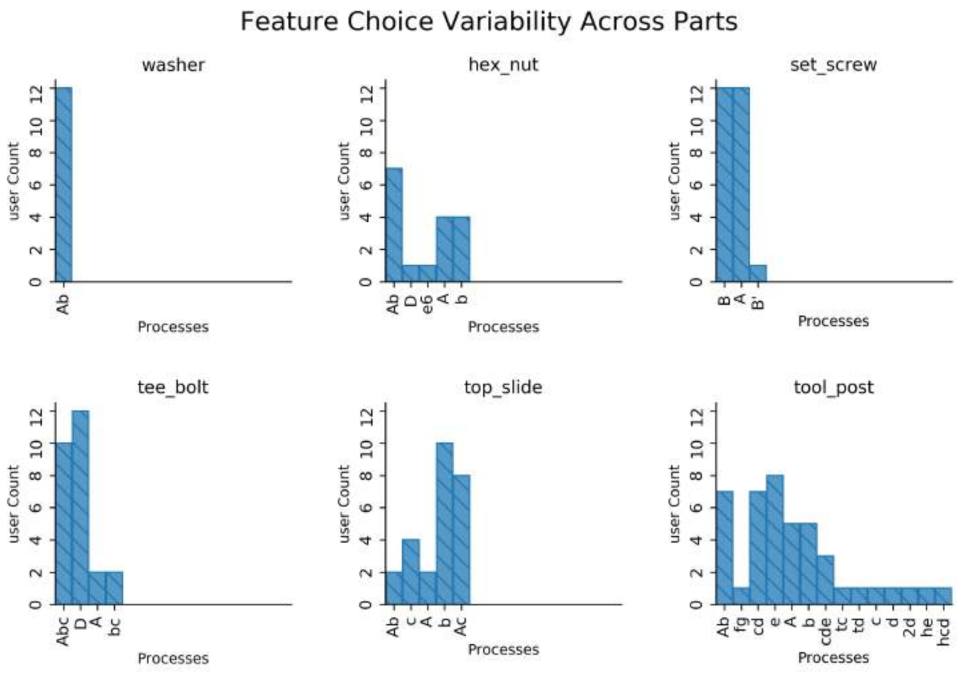


Figure 8: Feature count

Fig. 9 shows an evident variability in process choice even in files with a small number of features. There are limitations as the CAD modelling process must always start with an additive operation. It is essential to consider variability in an industry context still exists, but is controlled by imposing industry guidelines and standards to engineers [15]. Nevertheless, CAD software offers a vast number of options for solid modelling, giving rise to an array of different possibilities.

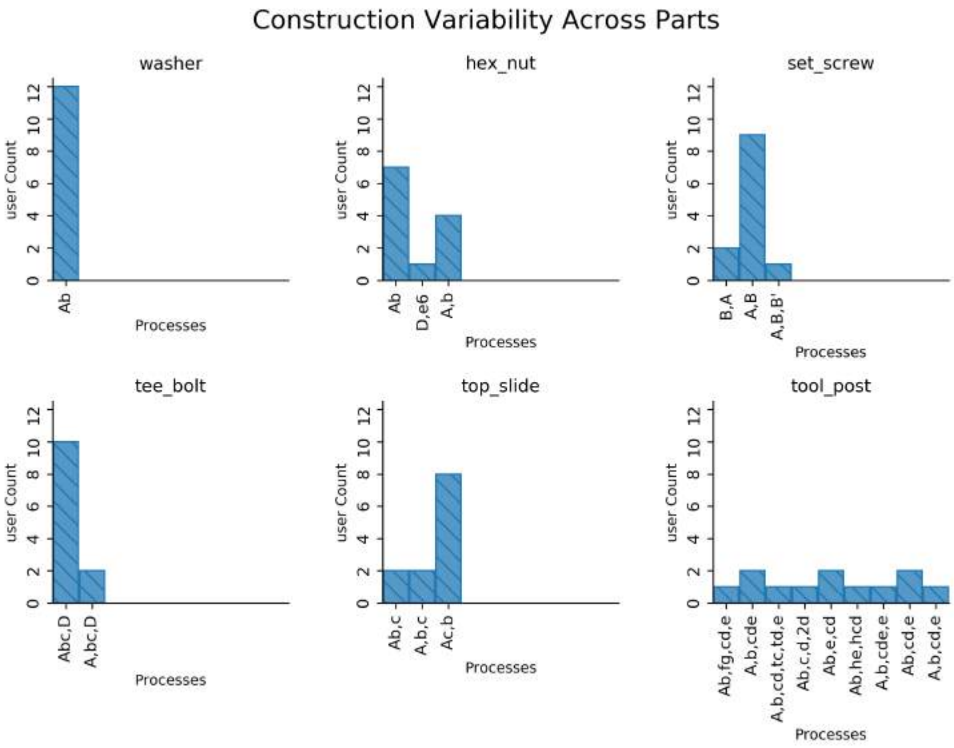


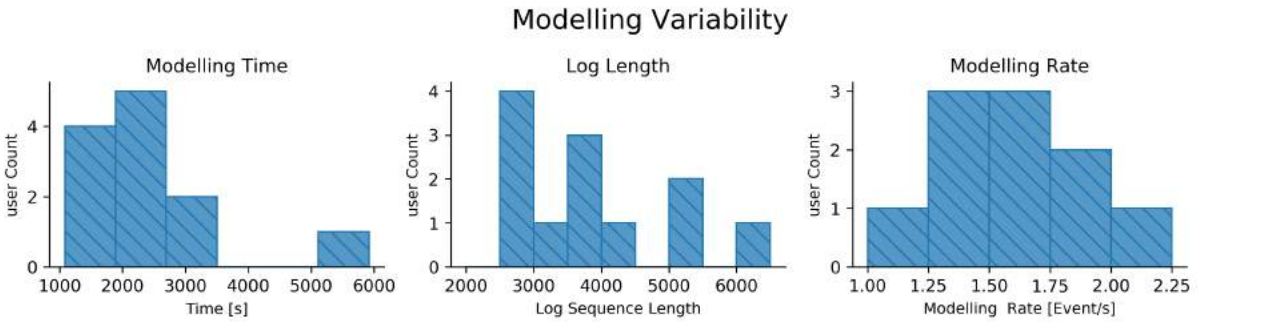
Figure 9: Modelling process variability

5.2 Modelling Process Variability

Through examination of the logs recorded during the experiment it was possible to highlight variability in: total modelling time and log length. This was followed by an appraisal of the variability in modelling rate, both across users and across parts.

Modelling times saw a range of approximately *5000sec/80min* (*2500sec/40min* excluding the outlier). Observing log lengths, the range is very large and shorter logs are less than half the length of the longer ones. The measure of the modelling rate has been estimated using the number of *events* that have been triggered throughout the modelling process. Log rates lie between 1.00 and 2.25 *events/s*. Fig. 10a shows the first evidence of variability in technique: variability in the time taken by the users to complete the task. Further inspection of the data reveals a variability in the number of *events* used to complete the same task (Fig. 10b) and consequentially the variability in the modelling rate (Fig. 10c).

In Fig. 11, user03 and user06 took a similar time to complete the task, but user06 invoked more than 500 *events* compared to user03. The same users compared in Fig. 12b created and edited 2D and 3D elements at a similar rate. This highlights how viewing, assembly and other type of *events* can influence the speed at which the user can complete modelling tasks. Comparing user02,user03, user06 and user11 in Fig. 12a, the



(a) Modelling Time (b) Log Length (c) Modelling Rate

Figure 10: Modelling variability measures

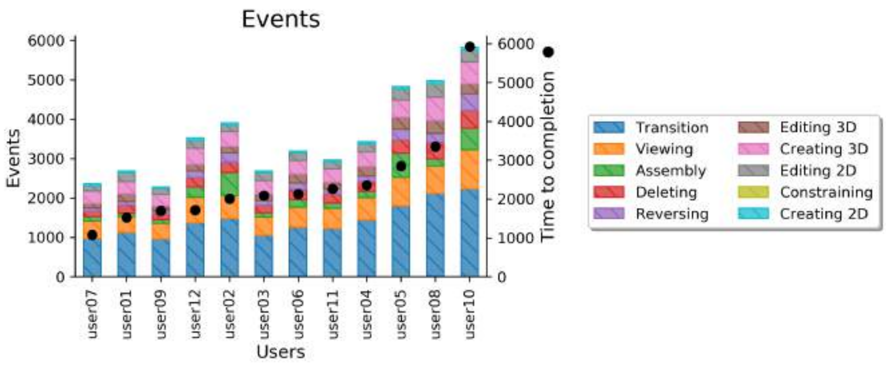


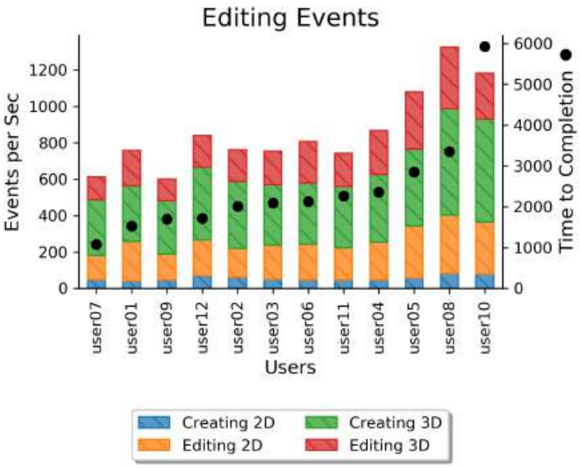
Figure 11: Cumulative *events* count compared across users

total number of *editing events* is similar, on the other hand Fig. 11 showed very different log lengths for these users. The users solved the problem with different approaches, perhaps undertaking the task with different mental models.

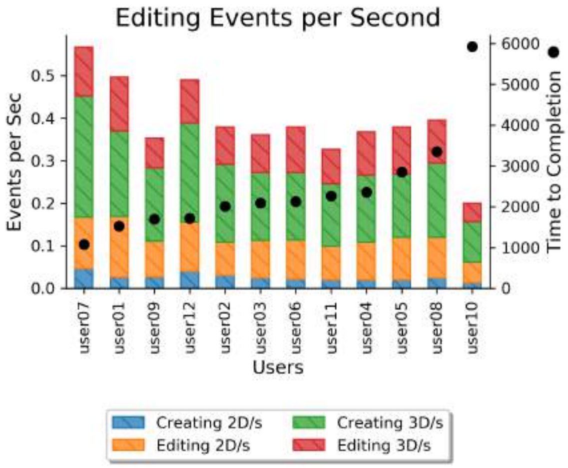
[11] explored how reversing and *deleting events* affect the length of a modelling transition matrix. Fig. 13 highlight a similar trend. Observing the number of *deleting events*, in Fig. 13a, among user03 and user06, the latter who was working at a higher rate, also had a higher number of *deleting events*. A similar observation, even if less evident can be made comparing user03 and user06 in Fig. 13b.

Conversely, user02 and user03 completed the task with user02 triggering more *deleting* and *reversing events*, yet taking less time than user03 (Fig. 13). Fig. 11 shows how user02 triggered 45% more *events* than user03, taking less time. Table 2 shows user05's dissimilar approach for simpler parts like the *hex_nut*, and more detailed design for more complex parts like the *tool_post*, in which they included threads. The impact of user02's decision on the editability of their parts will be discussed. Fig. 14 shows the *constraining events* triggered by some of the users.

Transition plots show how different user moves between different types of commands. Fig. 15 compares transition plot for two users who have similar CAD modelling time (user09 and user12). This plot is not scaled with respect to time and, of course, does not show when a user starts or stops thinking about the following



(a)



(b)

Figure 12: *Creating* and *Editing events* rate compared across users

event.

Transition plots provide an insight into the transition between the type of commands, but also in the amount of invoked commands within a type of *event*. Transition plots give an insight in the methodology and technique of the users, and enable a comparison among specific cases. Fig. 15 compares transition plots between user09 and user12. Some incongruities between the two process emerge. In particular, user12 who worked at a higher rate, shows in Fig. 13 a higher number of reverse and delete commands. Fig. 17 and Fig. 16 show transition matrices for respectively users with similar design time (Fig. 17), and the comparison between the fastest and the slowest user (Fig. 16). Note that the transition matrix for some user have empty rows and columns for constraining *events* as not all users used them throughout the modelling process (see. Fig. 14).

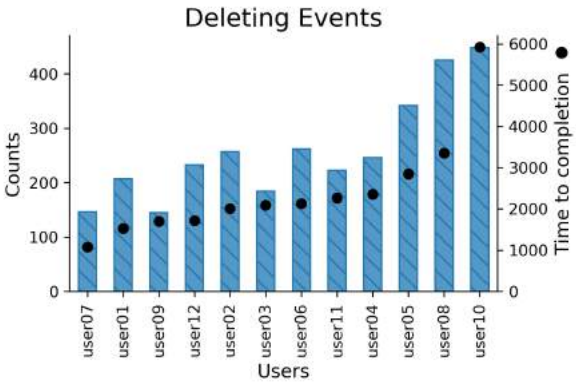
6 DISCUSSION: CAD MODEL VARIABILITY

This sections discusses the presence of variability in the CAD model, CAD modelling process and ultimately in the usability of the CAD model.

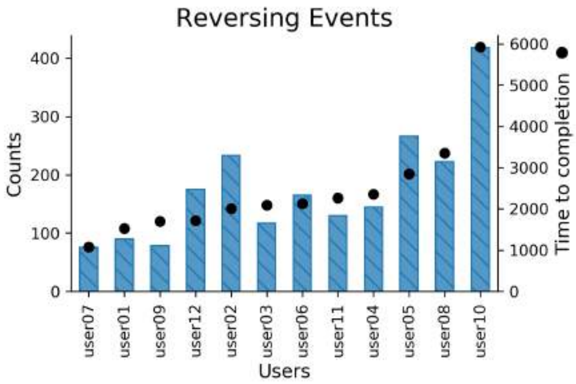
6.1 Model Variability and Modelling Process Variability

Looking at the properties of the completed files (Fig. 10) and in particular, at the end of the task illustrated in the first part of the Figure it can be asserted that variability in these cases arises because of the difference in Design Intent (Table 2), which continues throughout the construction process. That is, decisions taken during the construction process have a compound effect on the range of variance of the final models.

Further evidence in variability in technique can be seen by looking at the number of specific *events* taken by the users. (Fig. 11) shows both the total number of *events* taken by the users and the rate at which the users invoked a command in the Inventor environment. Considering the extremes, it is unsurprising to see that the fastest user invoked the least number of *event*, and worked at the highest rate, while the slowest user recorded the highest number of *events* (longest log), and also performed at the slowest rate. Even though there is a possible correlation between log length and time taken, as every *event* takes a minimum number of seconds to be performed, it is suggested by Suryanarayana et al. [29] and Ullman [30], that faster paced CAD modelling



(a)



(b)

Figure 13: *Deleting* and *Reversing Events* which usually characterise errors throughout the process.

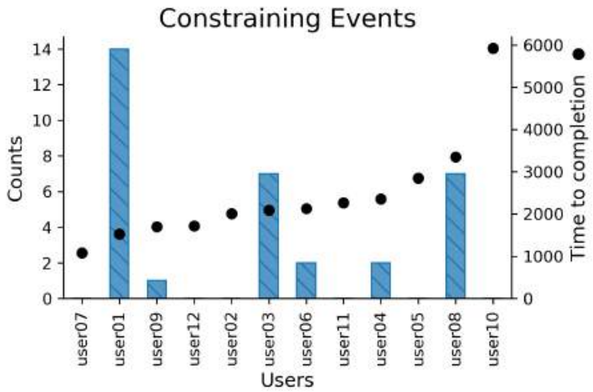
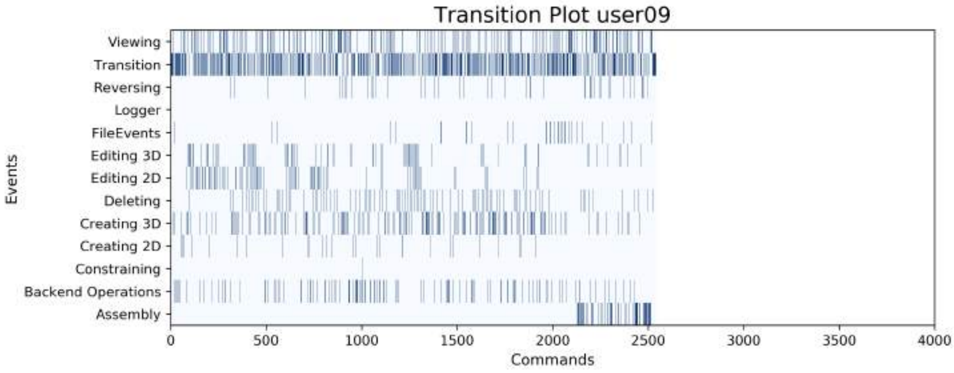


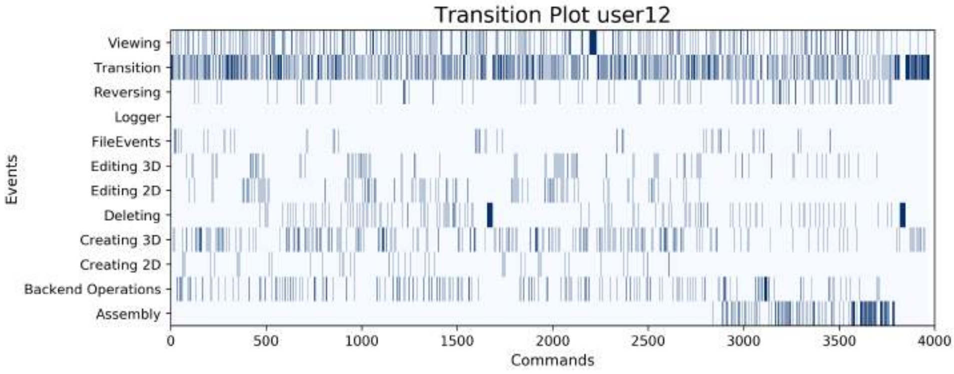
Figure 14: *Constraining Event* invoked by Users

does not necessarily lead to more editable models. As the task only rewarded the completeness and the speed of model construction, it is not surprising that Fig. 14 does not highlight any direct correlation between the time to completion and the *constraining events* count.

Comparing transition plots in Fig. 15 similarities in modelling approaches emerge. Both users (user09 and user12) invoked actions viewing and transitioning between environments, and only toward the end of the tasks did they both invoked actions in the assembly environment. The same users, with similar time to completion, are compared in Fig. 16. The users exhibit different methodologies that can be observed in transition matrices, and the transition sequence in Fig. 15 and diagrams in Figs. 11 to 13. These same figures suggest that the user with a higher pace (user12) approached the problem with a similar overall technique and methodology to user09. In particular, for the most complicated parts, user12 applied a similar design approach to the one adopted by user09, however the other parts were modelled using a more significant number of features and more complicated relationships which might have been the cause of the more significant number of *reversing events* also observed. Fig. 16a has a less distributed transition matrix than Fig. 16b, this can be interpreted as user09 working at a slower pace (Fig. 11 and Fig. 12), but with a more clear methodology than user12.



(a) User 09



(b) User 12

Figure 15: Command Transition plot for the user with the most similar CAD modelling time

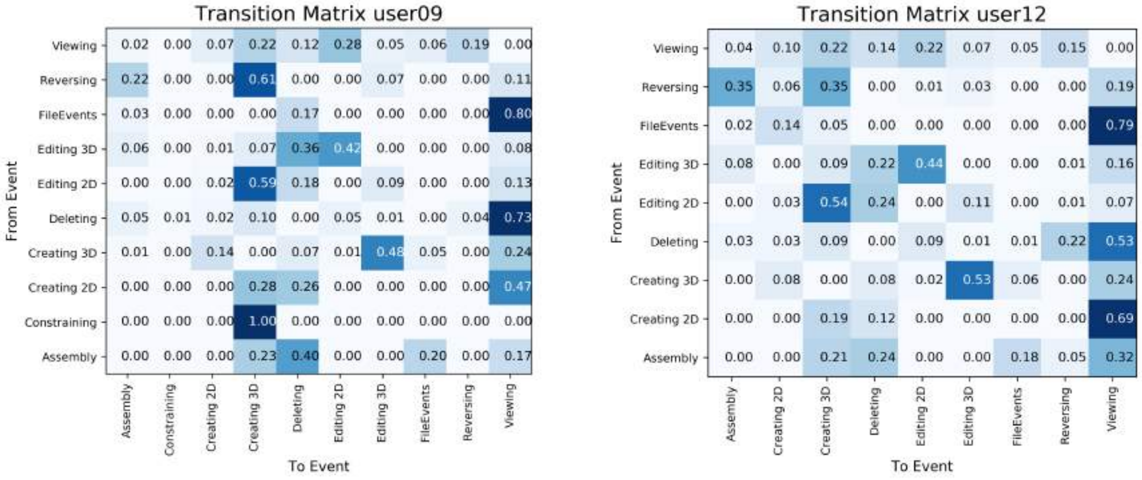
Fig. 17 compares the fastest and slowest users. Similarly to Fig. 16, one transition matrix (user07) is less distributed than the other one (user10). The authors hypothesize, that this might be caused by a clearer methodology being adopted by user07 who completed the task in less than 20% of the time taken by user10. Both users show a tendency to invoke *viewing events* after most other *event*.

6.2 CAD Variability Implications for Editability

Consistency [26] and Feature inspection [32] were used to assess variability in editability. Fig. 9, beyond showing process variability, they show inconsistencies across the different parts modelled in Inventor. This implies an underlying variability in editability of the models which will require further studies in order to be further evaluated. Fig. 11–17 show different levels of variability in the sequence of *events* which increase the chances of variability in the editability of the parts.

Hoffman [13] points out the importance of constraints and parametric design in CAD design. Thus, as part of the methodology it is also necessary to consider the *constraint events* invoked by the users. In particular, Fig. 14 shows that user01 was the most experienced user (information from sign up form) and this reflected on the methodology and techniques used in their modelling.

CAD model and CAD modelling variability affect the interrelation between the features. Being the building



(a) User 09 (b) User 12

Figure 16: Transition Matrix plot for similar design time

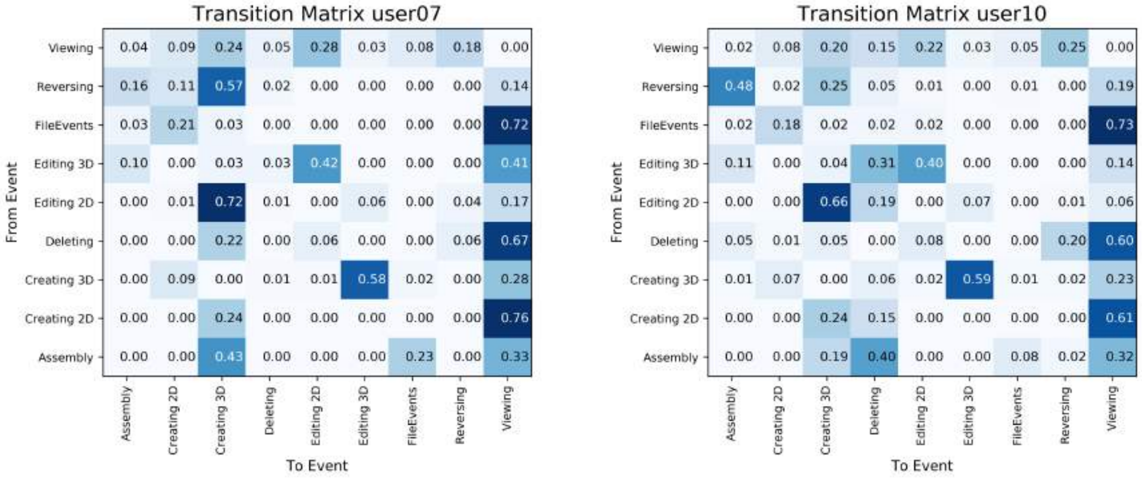
blocks of CAD models, their relationship has an impact on the efficiency and efficacy with which a user can edit a file. Thus they will have an impact on variability of CAD model editability. In extreme cases our results reveal that for visually identical models, user03 used a total of 15 features and user05 and user11 used a total of 11 features, Further, in the construction of visually identical models user09 invoked approximately 2200 *event* and user10 invoked approximately 5800 *event*. Such variation undoubtedly gives rise to variability in editability if only because different features are present and different sequences of features are presents.

6.3 Limitations and Future Work

The data collected in the experiment had resolution of *1 second*. This did not enable the analysis to extrapolate timestamps in order to construct time-series transition plots, as some entries had overlapping time series. For some *creating* and *editing events* it was possible to estimate an elapsed time as this might take more than a second. However, *reversing* and *deleting event*, which happen instantaneously in a programme, would take place at the same time as the following *event*, resulting in an estimated elapsed time of 0 seconds.

All models considered in the second part of the study were considered editable regardless of the variability observed, but the property which cannot be evaluated at the moment and how the observed variability would affect it. Several features and sketches, their organisation and relationship will have an impact on editability. Further study needs to be carried out in future to assess how different parameters affect the editability of a CAD Model.

The experiment recorded data about the CAD modelling process, and the logical progression is to undertake user studies to investigate (observe and measure) the variability in a CAD models' editability. This might include time, number of *event*and any required rework). Correspondingly, and based on the findings of this study, the Authors intend to conduct a future study aims at isolating the different parameters that affect the editability of CAD models and later to investigate whether these parameters/properties can be improved in order to make them more editable and ultimately reduce technical debt.



(a) User 07 (b) User 10

Figure 17: Transition Matrix plot for fastest and slowest users

7 CONCLUSIONS

This paper introduces the concept of usability in the context of CAD modelling as CAD model editability. It then progresses to analyse CAD models logged by [11] in order to explore and characterise variability in terms of approach, technique and methods. Then it progresses in discussing the derived editability of the CAD models. These findings suggest that it is possible to improve the editability of CAD models, possibly reducing future editing times and cost, and enabling easier collaboration among engineers.

7.1 Editability of CAD Models

Throughout the first section of this paper, the idea of usability, and editability have been considered, recontextualised and analysed in the context of solid CAD Models. CAD software manufacturers are already trying to manage the broader factors affecting the practical acceptability of a specific model, by offering platforms with interfaces which are widely spread and continuously maintained to improve user experience, efficacy and efficiency of drafters.

Assessment of editability of a model takes place during the design process, as the model will be edited until it can achieve all desired goals. Furthermore, continuously maintaining a model in a editable state does reduce the increase in technical debt, which is bound to rise over time.

7.2 Variability in CAD Models and CAD Models' Building

The second part of the paper uses data of CAD Models designed by users to get an insight into the existence of Variability. This part of the study is structured in two parts: CAD model variability, and CAD modelling process variability.

This paper shows multiple evidence in variability in different aspects of different models. Size, time, choice of features, and order of features are different across the same file when designed by different drafters. The variability in the final models emerges throughout the design process. Thus variability in the latter would affect the margin of variability in the CAD models' properties that were measured and considered [22].

7.3 Variability in CAD Models' Editability

The existence of variability in editability and in CAD models opens up the field to the question of whether it is possible to have a model which is more usable than others, and how this information could be used to improve the design process.

Using the logged data, it was possible to look at specific *event* and highlight the lack of correlation. Variability in feature choice and order, accompanied by variability in the CAD modelling process the analysed models leads to the conclusion that there is variability in the final models. Conversely, it is safe to assume that one model might have greater editability that another one. Additionally, we discussed editability, which will be the best measure for a more usable CAD Model in the discussed context. Given a specific context, it is possible to look at the quantifiable measure of a more editable CAD model.

This research informed not only on the existence of a more Usable model but on how quantities proving such variability can be used in future studies to analyse User Interaction in order to assess the editability of an object. Transition matrices can be used to asses not only the variability in design technique and method but also the editability of a model. A broader spread in the distribution of consequential *event*on a transition matrix when observing an experienced engineer can be attributed to a less usable Model.

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