Title:
Analysing the Variance and Sustainability of a Digital Thread

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Keywords:
Digital Thread, Stereolithography File, STL, Variance Analysis, Sustainability

DOI: 10.14733/cadconfP.2022.134-139

Introduction:
Digital transformation of engineering practice has accelerated the integration and automation of design processes. Changes in a digital asset[1] that defines, in part or in full, a design can now trigger automated workflows involving a range of Computer Aided Engineering (CAE) tools[2] to validate features such as performance, manufacturability, cost and sustainability. This is referred to herein as the Digital Thread.

The enabling capabilities for integration and automation have been achieved through considerable research and development of CAE tools. However, variance of the data and information flowing through the Digital Thread due to the: compound assumptions made across the tools and toolchains (e.g., mesh type, mesh density and solver selection); fidelity of the representation exported/imported between tools (e.g., whether to include the fillets within the model to be meshed); and, type of data format used in data transfer (e.g., use of STEP or STL file) is less well understood. This is a concern for many practitioners as it leads to design uncertainty with inaccurate simulation results and manufacturing profiles, and in extreme cases solutions not being resolved.

Further, the Digital Thread poses a concern for sustainability as these automated workflows can lead to a considerable use of compute resource which impacts the carbon footprint of the design process. Thus, it is important to consider that the input and subsequent translation of information along the thread is valid and performed in a computationally efficient manner, and the design insights generated can offset the resource use.

To advance the community's understanding, this paper explores the variance and sustainability of a thread that generates and exchanges Standard Tessellation Language (STL) files. STL file export has been selected because it is one of the most prolific and common formats for data exchange. STL files are often used in Computer Aided Manufacture (CAM) software to generate G-Code for Additive Manufacturing (AM) and in mesh generation for simulations, such as Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and Multi-Physics.

The paper continues by providing an overview of the related work. This is followed by the study design to evaluate an STL-based thread. A subset of the results and a discussion on the variance and

[1] For example, a Computer Aided Design model or design parameter spreadsheet.
[2] For example, Computer Aided Manufacture, Finite Element Analysis and Computational Fluid Dynamics.

sustainability of the thread is then presented. That paper then concludes with the key findings and opportunities to broaden the study to other forms of Digital Thread.

Related Work:

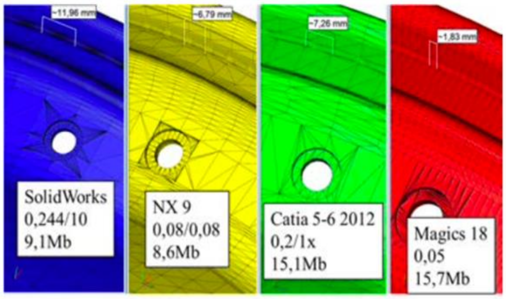
The Digital Thread provides a framework to describe the different types of data and information flow in an engineering organisation. [3] review of industry literature developed a Digital Thread definition and identified the types of thread, benefits and technologies being used by industry. The Digital Thread was defined as a "*data and/or information flow between systems and/or people that is systematic, consistent and auditable delivering the right information at the right time to the right people through the right mechanism*". The seven types were: *Internet-of-Things*, *Twinning*, *Operational*, *Exposing Digital Assets*, *Business Intelligence*, *Lessons Learned* and *Inter-Organisational*.

The threads of interest in this paper are *Operational* threads where the data and information flows serve to enhance productivity and efficacy of an organisations' operations. In this context, we're developing workflows that automatically update and perform simulations that depend on CAD geometry. By connecting and automating these workflows, we place assumptions on the consistency of the data being exported and imported by our tools and that it does not have a significant effect on the downstream processes.

While the analysis of STL file exchange in the context of the Digital Thread is new, generic variance analysis of STL files has been performed. [4] evaluated the STL file export of six CAD systems for CAM of Additive Manufactured parts. The models evaluated were of a primitive cylinder and revolution representing a wheel rim. The results highlighted that the default export settings were not appropriate, and the visual comparison highlighted different polygon compositions that formed the overall geometry (Fig. 1a). This led to the hypothesis that these variance could introduce uncertainty into a thread as well as leading to threads being more or less computational expensive to run.

However, evaluating the composition of geometry is non-trivial as highlighted by [5] who reviewed methods for comparing geometry (Fig. 1b). They recommend performing a broad assessment across a range of metrics to identify the areas of variance, reflect on the areas of variance and their significance for the intended purpose, and perform a further, more focused, analysis on the features of interest.

In terms of the sustainability of threads, the authors were unable to find any work concerning CAE workflows.



(a) Metadata and visual comparison [4].

	Insensitive to modelling history	Independence of format	Sensitivity to minor differences in solid models	Sensitivity to scale	Deterministic
2.5D Spherical Harmonics [24]	✓	✓	✗	✓	✓
Light Field Descriptors [7]	✓	✓	✗	✓	✓
Surface area and volume [7,35]	✓	✓	✗	✓	✓
3D Shape Histograms [19,35,37]	✓	✓	✓	✓	✗
Solid Angle Histograms [7]	✓	✓	✓	✓	✗
3D Spherical Harmonics [7,24]	✓	✓	✗	✓	✓
2D Shape Histogram [7,35]	✓	✓	✗	✓	✗
Convexhull Histogram [7,37]	✓	✓	✗	✓	✗
Geometric Ratios [7]	✓	✓	✗	✓	✓
Principal Moments [7]	✓	✓	✗	✓	✓
Moments of Inertia [7]	✓	✓	✗	✓	✓
Crinkliness & Compactness [7]	✓	✓	✗	✓	✓
TAD [2,36]	✓	✓	✓	✓	✓

(b) Methods for comparison [5].

Fig. 1: Comparing exported CAD geometry.

Experimental Set-up:

The experiment followed a two-stage process. Stage One examined the composition of STL files exported by two CAD systems – Autodesk Fusion360 and Dassault Systèmes CATIA V5. Two CAD model designs featuring a range of geometric features were selected from [2] to identify whether different geometric features have greater variance than others (Fig. 2). Default settings were used for the file export.

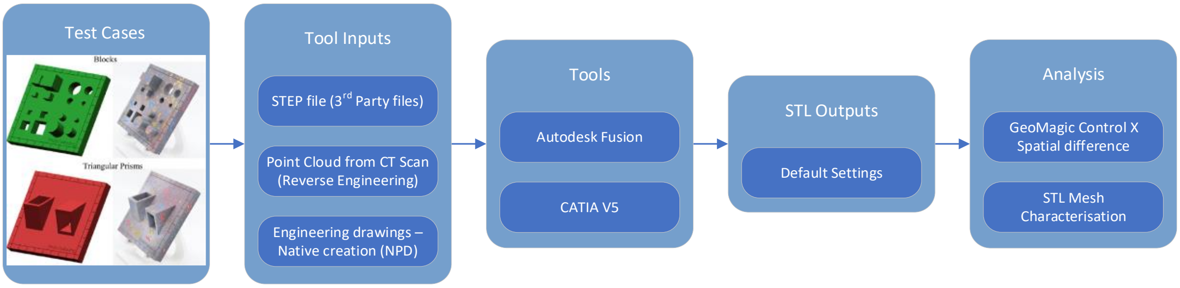


Fig. 2: Experimental Set-Up.

Three scenarios in generating the STL file to be send through the thread:

1. **Supplier Provided File:** The models were created natively in each CAD package and then exported as a STEP file. This formed the "input" as if the model was provided by a supplier. The design engineer would then open the STEP file in their CAD program and export as an STL file.
2. **Reverse Engineering**: The models were 3D printed and then CT scanned to provide a point-cloud. The data was imported into the CAD programs and a solid model formed and exported as an STL file.
3. **Native Design**: An engineering drawing and image of the models were provided to design engineers competent and experienced in each CAD program. They were then tasked with re-creating the model and exporting it as an STL file.

This resulted in six STL files of the same geometry that could theoretically be the input to the thread. The metrics used to compare the STL files were: number of vertices and edges; surface area; orientation; scale; file size; format; triangle area distribution and interior angle distribution.

The second stage examined the compound computational effort of a thread using an STL file as the data exchange mechanism. OpenSCAD was used to create a sphere of increasing fidelity using the in-built 'fn' quality variable. The sphere was then exported as an STL file and fed into a CAM package – Cura – to generate the G-Code for AM. The time and size of data exchange was recorded. 10 trials were performed with the average taken.

Results:

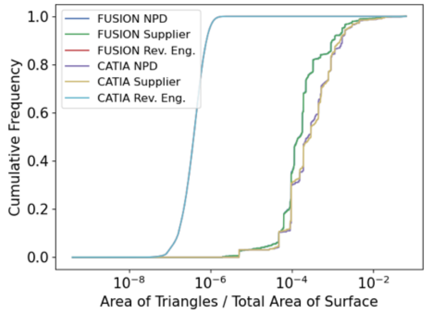
Tab. 1 provides the summary statistics of the six STL files. Surface area was consistent across all the STL files. However, variations in whether the STL file was in a binary or ASCII format based on CAD package and resulted in different file sizes. This is an important consideration as binary formats can provide savings in terms of disk space and network traffic but at a loss of human-readability.

The *NPD* and *Supplier* STL files provide comparable results indicating both CAD systems are capable of handling CAD neutral formats without effecting the generation of the STL file. The only item of note is the translation of axes. While a 'human-in-the-loop' thread could correct this, an automated thread would have to be configured to check for this as it could result in errors in simulation processes. The *Reverse Engineering* scenario also highlights that a change in scale can occur. Thus, for a reliable and resilient thread that can accommodate the different scenarios, checks and translations will need to be put in place. In addition, the statistics indicate the composition of the *Reverse Engineering* STL file is significantly different to that of the *NPD* and *Supplier* scenarios and may affect downstream processes.

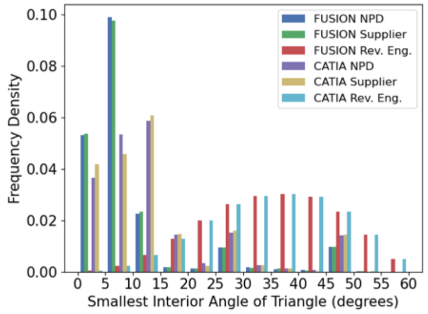
Fig. 3 presents the results from the analysis of the areas and interior angles. In both cases, the *Reversed Engineered* STL files differ considerably with an even distribution of similar sized triangles while the STL files from the CAD packages feature an almost bi-model distribution of large and small triangles. Such differences may affect downstream processes in the thread (e.g., FE meshing/remeshing of geometry and must be checked if the input scenario changes). While the tools introduce variance, there is little to no difference between the *Supplier* and *NPD* scenarios, which provides confidence in today's interoperability of STEP exchange. Thus, organisations may not need to be concerned with regenerating the geometry in their CAD native format.

Tab. 1: Analysis of STL export.

	Plate One (Cube and Cylinders)					
Scenario	**NPD (Native)**		**Supplier (STEP conversion)**		**Reverse Engineering (CT)**	
CAD System	**Fusion360 (Ref)**	**Catia**	**Fusion 360**	**Catia**	**Fusion360**	**Catia**
Vertices	896	576 (0.64)	896 (0.00)	576 (0.64)	1,130,924 (1262)	1,130,924 (1262)
Edges	2706	1746 (0.64)	2706 (0.00)	1746 (0.64)	3,392,790 (1253)	3,392,790 (1253)
Surface Area	99,406	99,387 (0.99)	99,406 (0.00)	99,387 (0.99)	**3,034,700 (30)**	30,347 (0.30)
Orientation	(0,0,0)	(0,0,0)	**(90,0,0)**	**(90,0,0)**	(0,0,0)	(0,0,0)
Scale	1	1	1	1	**10**	1
Size [MB]	0.0882	**0.318 (3.6)**	0.0882 (0.00)	0.318 (3.6)	108 (1224)	**602 (6825)**
Format	Binary	ASCII	Binary	ASCII	Binary	ASCII
Feature	**Plate Two (Triangles)**					
Vertices	324	324 (0.00)	324 (0.00)	324 (0.00)	1,340,994 (4138)	1,340,994 (4138)
Edges	978	978	978	978	4,023,003	4,023,003
Surface Area	102,242	102,243 (0.00)	102,242 (0.00)	102,242 (0.00)	3,133,931 (30)	31,339 (0.30)
Orientation	(0,0,0)	(0,0,0)	**(90,0,0)**	**(90,0,0)**	(0,0,0)	(0,0,0)
Scale	1	1	1	1	**10**	1
Size [MB]	0.0319	**0.178 (5.58)**	0.0319 (0.00)	0.178 (5.58)	128 (4013)	**714 (22,382)**
Format	Binary	ASCII	Binary	ASCII	Binary	ASCII



(a) Distribution of Triangle Areas (Plate 1)



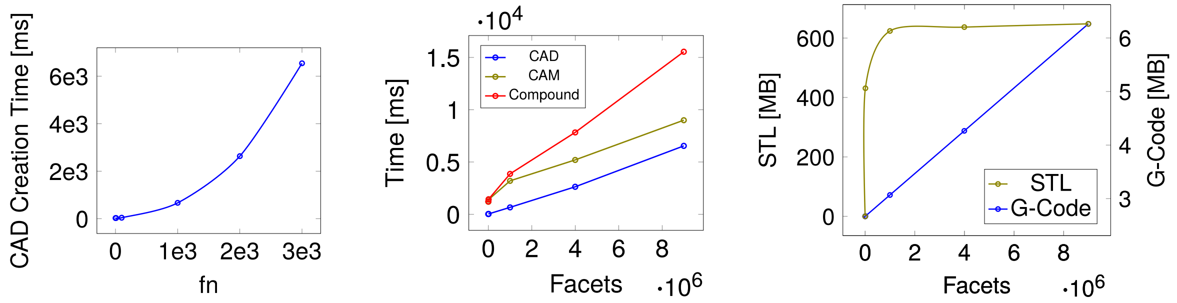
(b) Distribution Interior Angles (Plate 1)

Fig. 3: STL Export Comparison.

Fig. 4 presents the results from the sustainability study. Fig. 4a reveals that, from a user's perspective, the computational effort polynomial scales as they change the 'fn' parameter. Although, if one looked at the thread from the perspective of the number of facets in the STL file, the computational effort scales linearly (Fig. 4b). This highlights that we need to be aware of the parameters that we will be using to drive a thread. The downstream CAM process also scales linearly with respect to the number of facets. Fig. 4c shows the storage footprint against increasing model fidelity. It shows that beyond ~$1.5\text{x}10^6$ facets, there is little to no size increase of the G-Code file. Further inspection of the G-Code file revealed a convergence on the generated toolpath. Therefore, the additional computational resource required to make the higher fidelity STL file provides no additional gain in design insights or output quality for the CAM process.

Discussion:

The comparison of the STL file export reveals that all methods of exporting the geometry to STL offer a good resolution to the idealised geometry with very little variation across the scenarios. However, taking a closer look at the STL file composition reveals variation in the tessellation. CAD packages feature a peaked distribution of small triangles around key features and larger triangles for the face areas while the STL file from the *Reversed Engineer*ing process are evenly distributed. It is encouraging to see that there was little difference in the *NPD* and *Supplier* scenarios indicating that STEP geometry can be accepted as the input without fear of it leading to significant downstream effects to structure of the STL file being exchanged. However, the differences exhibited in the *Reversed Engineering* scenario may have significant effects on down-stream processes such as meshing for FEM and CFD. This will need to be reviewed by an organisation if they were to change the input scenario.



(a) User-driven creation time (b) Computational Effort (c) Computational Storage

Fig. 4: Compound Computational Effort.

Having characterised the variability in STL file export, future work includes: expanding the STL analysis to a greater number of CAD packages and models; examining whether the same STL structures can be attained from different vendors through manipulation of the export parameters; examining the variance produced from simulations that use the STL file (e.g., CAM processes); examining the variance in the mesh files produced from a set of industry standard mesh tools that accept STL files as the input; and, examining the simulation results that use the mesh as an input.

The analysis also highlighted the sustainability of a thread with it exhibiting linear compute scaling across the two-stages. Although one must be aware of the control variables as it may be that they result in a polynomial or other degree of scaling. As our threads increase in length with the addition of more tools as well as parallel activities (e.g., CAM check and CFD performance check), organisations will have to remain vigilant of this compound computational effect. This is to ensure that the automated workflows, auditing, and compliance processes are robust, sustainable, and cost effective. Future strategies could include the optimal sequencing of checks to avoid over-computation as well as performing checks at different levels of fidelity.

Conclusion:

Digital transformation of engineering practice is enabling the creation of digital threads of data and information being passed amongst tools and processes. The example described in this paper is of CAD-driven design processes where an update to a CAD file initiates a set of simulation processes that report back on whether the design still conforms to the design requirements. However, there is currently little understanding of how the compound assumptions and processes through the thread could lead to uncertainty in the output. This paper demonstrates that variance does exist in the geometry exported by our tools and is affected by input, vendor, and export settings. Additionally, computational effort can easily be expended without additional insight being produced by the thread. Thus, industry and academia need to be aware, record and evaluate the variance and sustainability of their Digital Thread.

Acknowledgements:

The work is part of the Engineering and Physical Sciences Research Council (EPSRC) grants – EP/R032696/1 and EP/V05113X/1 – and Digital Engineering Technology & Innovation (DETI) project.

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