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SHAPING THE COMPLEXITY OF A DESIGN

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ABSTRACT

This paper presents an introduction to concepts of complexity in support of assembly-oriented design, to guide the designer in creating a product with the most effective balance of manufacturing and assembly difficulty. The goal is to provide the designer with such information throughout the design process so that an efficient design is produced in the first instance. In this paper, the range of definitions and applications of the term 'complexity' are reviewed and then definitions appropriate for the situation are selected. The metrics required for comparison of variants of different complexity is discussed. Finally, a research agenda is presented for development of the proposed metrics within the Designers' Sandpit project.

KEYWORDS

Complexity, Product Design, Assembly, CAD, Geometric Reasoning, DFA

INTRODUCTION

Complexity has captured the interest of scientists and engineers for many years, and their attempts to gain an understanding can be seen in the various definitions given to it. Information processing systems and social systems are studied in such a way that their overwhelming 'complicatedness' requires methods to break them down into a more digestible view, hence the need to define and measure complexity.

In terms of manufacturing processes, assembly costs and quality of the end product, complexity plays a vital role in the achievement of the best design that not only takes into account the assembly planning but also the selection of the most suitable manufacturing process.

The Designers' Sandpit research project [1] makes use of design evaluation tools such as Design For Assembly (DFA), which have demonstrated some success in reducing problems such as redesign, rework and a lengthy product introduction period - mainly resulting from traditional trends of using component-oriented CAD tools rather than dealing with a product as a whole. The main goal is to develop an environment for "Assembly Oriented Design" incorporating methods for the generation and evaluation of concept design ideas, manufacturing analysis, assembly planning and design advice.

One outlook of this work is the development of means to quantify the complexity of a product and the definition of measures to be used in conjunction with other metrics and enable comparison of shape similarities.

Unfortunately, little has been achieved in the area of complexity metrics that can be used in a sensible way. One survey by Tang [2] shows that from a series of studies, only 20% have attempted to produce some sort of quantification, thus considerable further research is required to make complexity a practically useful concept.

This paper presents a review of current achievements in the task of defining specific complexity metrics and proposes their integration with design evaluation tools such as DFA. More specifically, in this paper, shape complexity metrics will be targeted as an appraisal of the fundamental purpose of the manufacturing analysis. The paper is organised as follows.

Section 1 introduces some attempts to define complexity 'as-is' and the limitations of such efforts. Section 2 reports state-of-the-art methodologies conceived to tackle the complexity issue in design. Section 3 highlights considerations of complexity in the Designers' Sandpit. Section 4 presents the theoretical considerations in our research. Section 5, on the other hand, presents the Sandpit's requirements to accomplish successful complexity metrics. In Section 6, a research agenda to meet the current project requisites is presented, finalising this paper with conclusions in Section 7.

NOMENCLATURE

In this paper the following nomenclature has been defined in order to explain the metrics of complexity:

- n – Number of components,
- C_m – Manufacturing complexity,
- C_p – Process complexity,
- C_{st} – Structural complexity,
- C_s – Sequence complexity,
- C_T – Overall complexity (threshold),
- $w_1, w_2 .. w_i$ – Numerical constants.

1 DEFINITIONS

The definitions of Complexity *per se* are as diverse as the world that it involves. A quick browse of the Internet yields thousands of pages related to complexity, ranging from the very strange, up to the most engaging explanations.

These characterisations can be classified according to references dealing with the concept and measurements of complexity. Amongst the sciences that deal with the theory of complexity we can take into account: *Chaos Theory* (very fashionable in the last few years), *Fuzzy logic, Networks, Philosophy, Psychology, Statistics* and so on. The list is enormous and some definitions are very intriguing. These and other references to measures of complexity have been carefully compiled in a bibliography by Edmonds[3]. It follows that there are some considerations of particular relevance to this paper in sciences such as:

- **Arithmetic** – (1) The number of arithmetic operations needed in a computation – (2) the level in the arithmetic hierarchy.
- **Entropy** - Complexity is defined as the rate at which predictability disappears.
- **Games**: Measures of strategic complexity for games, based on the idea that strategies requiring more detailed information are more complex.
- **Information**: Effective complexity defined as the algorithmic information complexity of an ensemble of patterns.
- **Software**: The "complexity gap" as the region between a top-down specification or planning process and the highest level of software tool available.

In a further report [4], Edmonds noted that any general estimations of complexity are necessarily abstract and complexity can only be attributed to models of specific processes in any given language.

Simon [5] also expressed such an idea. In a series of observations about complex systems and the architecture of complexity, he highlights some common characteristics:

- Complexity of a system depends critically upon how it is described.
- Most complex systems contain a lot of redundancy.
- Simplicity of description can be achieved by finding the right representation.
- Hierarchies of complex systems can often be described in economical terms; that is to say, redundant components can be grouped together and considered as integrated units.

These characteristics of complexity deal with the system as a whole and, as he states, such a system is made up of a large number of parts that have many interactions.

It follows that many complex systems are based on hierarchies. A complex system defined as a *hierarchic* one has the advantage of being a traceable configuration. If a complex system is based on a simple structure with redundant and non-redundant parts continuously added to it, then having a finished system is nothing but a chain of built-in features. The lower level is considered the basis and, to build up the system, it is necessary to add redundant, but necessary, extra levels. This idea fits in perfectly with an assembly-oriented design environment, where all parts must interact with each other at some point, but perform different functions. It also provides the basis for an algorithm to tackle this task when evaluating the shape complexity of single parts, as discussed in more detail later.

2 PAST STUDIES

The written definitions and terminology related to complexity offer an insight of the fields where it has been studied. Conceptual definitions are more often encountered in design, whereas quantitative methodologies are frequently related to manufacturing. For the purposes of this paper and without loss of generalisation, the studies reviewed have been classified into: conceptual (design) and mathematical models of complexity. An additional section on quantification of shape complexity has been emphasised for reasons that will become clearer as the discussion evolves.

2.1 Complexity in design

Complexity in design is generally considered in relation to component geometry where it has been studied for its influence in many areas. This research can be classified according to the following categorisations: geometry, topology and assembly.

2.1.1 Geometry

In applications such as computer graphics and finite element mesh generation, polygon meshes are defined in terms of the geometry (coordinate values of vertices of the meshes making up the model) and connectivity of the object (the relationship amongst the vertices that define the polygonal faces of the mesh) [6]. Several algorithms for triangulation of the mesh have been used and, in some of these, shape complexity is a factor for determining the resolution [7]. Informally, this notion of shape-complexity measures how entangled a polygon is.

Other studies have examined the nature of data exchange through the Internet and between different modelling platforms [8, 9]. Compression of the model topology involves reducing redundant references to vertices and edges that are shared by many entities. The compression of geometric data requires the precision of coordinate values, normal vectors, etc. to be reduced and this is often achieved using techniques from signal processing. This is required in order to reduce file sizes. Model complexity in this context is used to establish the optimum compression algorithm for the particular model to ensure a minimum loss of information.

Another overlapping consideration of complexity in design is that of "CAD Complexity". In a study by Chase and Murty [10] not only is the geometric complexity of the CAD model considered, but also the complexity of the CAD file system of organisation and the operational complexity of the CAD software in terms of its functionality. The notion of a hierarchical CAD file system corresponds well with the traditional model in design of a product structure tree.

2.1.2 Topology

Kyprianou [11] pioneered feature recognition techniques for the purposes of classifying shape for automated part coding, but since that time, feature recognition has been applied to many aspects of design, and different measures of complexity have been established depending upon the precise application.

Part Coding is based on the manufacturing philosophy of Group Technology Part Codes, in which similar parts are identified and grouped together for the purposes of generating manufacturing plans and scheduling production. The process is automated using CAD data as input [12] and enables re-use of existing manufacturing process plans or provides a starting point for generation of a new plan. Some systems provide a 'fuzzy' search facility based on an index of 'similarity' between the required set of features and those recorded for each part in its catalogue. The similarity index is based on a comparison of part codes and considers both features in common and those that are absent [13].

The 3Dsearch.net project at Heriot-Watt University uses algorithms to assess the geometric similarity of 3D models and applies it to the Internet sourcing of engineering components [14]. Within this and similar work, considerations such as the number of faces in a model, number of sides of a polygon, curvedness, symmetry, number of turns, degree of compactness, angular variability and crinkliness have all been used to compare aspects of shape complexity [10, 15].

Yet another interpretation of complexity is aimed at the feature recognition research community themselves, to compare the effectiveness and reliability of different feature recognition algorithms. One such algorithm is presented by Little *et al* [16] who attempt to generate a complexity code for an object in terms of the number of face types: their relative orientations and interactions (local complexity) and their distribution across the object (global complexity).

2.1.3 Assembly Analysis.

Although the focus of 'complexity' research in design has been in relation to component geometry, some attempts have been made to quantify the complexity of an assembly.

Goldwasser [17] defines 'virtual assembly sequencing' as the separation of specific geometric assumptions from the assembly sequencing, turning it into a graph-theoretic problem focused on the combinatorial aspects of feasible assembly sequences.

Similarly, Wilson and Latombe [18] define product complexity as the lower-bound complexity of all feasible assembly sequences. The complexity of each assembly sequence is evaluated in terms of the insertion trajectories, the number of hands required and the gripping configuration during component assembly operations. The number of assembly operations is also considered.

2.2 Specific complexity measures.

The methods described in the preceding section do not address specific measures of complexity. However, in some disciplines more precise metrics have been developed.

Despite being apparently more conceptual than concrete, in terms of figures, Suh [19] defines complexity in the field of *axiomatic design*[1], subdividing it into *time-dependent* and *time-independent complexity*, and as if that were not enough, there is a further subdivision for time-independent complexity into *real* and *imaginary complexity* being both completely orthogonal and forming a vectorial sum of absolute complexity.

The real complexity is regarded as the uncertainty in fulfilling the functional requirements of a design. Once the

[1] For further reading, refer to Suh NP (1990) 'The principles of design'. Oxford University Press, New York

problem has been defined, the design parameters form the set of factors that will be used to minimise the real complexity. As soon as the real complexity has been reduced, the design is expected to meet as many functional requirements as possible, given the appropriate definition of the design parameters. Imaginary complexity, on the other hand, is held as the lack of understanding of the system designed giving the impression of a complex system when in fact it is not.

The numerical relation between the functional requirements (FR) and the design parameters (DP) is given by the probability of finding the right combination of any DPs to satisfy the entire set of FRs. The complexity (real complexity) is given as a function of the information content for satisfying a number of FRs.

Time-dependent complexity is due to uncertain future events that cannot be predicted *a priori*. This type of complexity, which is not clearly related to product design, won't be extended in this paper. Sorry to say, this leaves the time-independent complexity as the first approximation to define complexity metrics in designing systems; this however does not fulfil the requirements of our research.

Nevertheless, complexity has been studied in other type of systems. In the area of manufacturing systems for instance, Calinescu *et al* [20] have surveyed the field of complexity for a more tangible definition of it and also proposed some formulae for its assessment. Their study and work is based on entropic measures of information, divided into static (structural) and dynamic (operational) aspects of complexity. Their paper presents the complexity of a system as directly proportional to the 'amount of information needed to describe the state of the system.' The structural complexity accounts for the resources and their state; such measure can be used in scheduling those resources. The dynamic complexity, on the other hand, accounts for the behaviour of the system and is used for monitoring a manufacturing facility. They finally propose a methodology for measuring the complexity of manufacturing systems and their supply chains. Sadly, the research is directed more at management of the manufacturing processes, rather than the details of the processes themselves and therefore cannot be directly related to the product design, as required by our research for the Designers' Sandpit.

Another view of systems complexity is that given by Tang [2] in adaptive design. In this paper, the author stresses the lack of theory, foundations and software to support complexity metrics. He proposes a qualitative differentiation between '*architected complexity*' and '*complicatedness'*; the first one being a beneficial property of systems provided it reduces such complicatedness. He devises a formula in which complexity is a function of the number of elements, their interactions and the *bandwidth*[2] amongst the elements of the system. This function increases monotonically, provided the system size, interaction of elements and bandwidth increase as well. Complicatedness, on the other hand, is the measure of the capacity of the system to handle its own complexity. As a result, complicatedness is a function of complexity with an asymptotic behaviour until it reaches a point of saturation; thereafter the system enters a stage of unmanageable complicatedness. This growth pattern commonly occurs in fields such as biology, engineering and economics.

2.3 Evaluating shape complexity in the DFA world

Measuring shape complexity is not a new concept; it is not even enjoying a new boom now that the computer power has been increased. It has been thoroughly explored in 2D objects [7] and for considerations of shape similarity for image retrieval systems [21], but it has not been fully explored in 3D models and even less in the DFA environment.

Some complexity factors have been suggested for specific processes, such as the one proposed by Tomov [22]. He presents a new shape complexity factor for forged parts based on FEM analysis and considerations of the amount of volume transformed between two arbitrary states. Despite its quantifiable nature, the factor is not suitable for DFA and, therefore, it is not useful for the intended scope of the Designers' Sandpit environment.

On the other hand, Kim *et al* [23] obtained a fully quantifiable factor and, even better, it is DFA oriented! Their factor is based on the feedability of parts, which is in itself based on old stochastic parts feeding algorithms reported in the same paper. This approach consists of a feeding mechanism (a device with a gripper that can orient parts under software control) and the planning algorithm. The algorithm recognises the grasping plans based on geometric properties, namely their polygonal contour. The variables considered are the initial and final orientations. Since the initial part orientation is uncertain, then the first actions consist of selecting random orientations in order to grasp the part. This process is repeated until the part is correctly oriented. The mathematical model is based on probabilities and transfer functions that take the first action as a probabilistic distribution of all potential orientations. The feedability of the part is based on the number of steps necessary to orient the part and reach a plan with stable grasping orientations. In spite of its attempt to provide a shape metric of the part, this technique has two major drawbacks. Firstly, it is based on probabilistic measures, which leaves no room for a geometric reasoning approach. Secondly, it is dependent on the orientation of the part to find its symmetry and try to match that of the gripper. This condition of 'orientation required' has been re-evaluated and dismissed by Tate [24] in studies of symmetry detection using geometric reasoning.

[2] Alas, in this context the definition of bandwidth is rather vague.

Thus considerable further research is required to make complexity a practically useful concept within the Designers' Sandpit environment. (See *Sandpit Requirements*)

3 COMPLEXITY IN THE SANDPIT

3.1 Overview

The design process supported by present CAD tools tends to be component-oriented rather than dealing with a product as a whole. This leads to redesign, rework and a lengthy product introduction process. Design evaluation tools, such as Design for Assembly (DFA), have demonstrated some success in reducing these problems, but these can only be applied once a complete product description is available and hence the potential benefits of early analysis are not realised. A more proactive approach to DFA [25] requires support for assembly planning during the design stage and this is one aspect of the research that the Designers' Sandpit seeks to address.

The Designers' Sandpit environment is based on the idea that a large proportion of all product costs are determined at the design stage and much of this cost is incurred during assembly. In fact, there is evidence to suggest that in industry, products are still designed with at least 50% [26-28] excess of parts and assembly content and undergo more complex assembly procedures than is necessary. Thus, the designer needs to consider assembly whilst developing product design in order to mitigate subsequent problems on the shop floor. It is now accepted that product assembly considered at an early stage of the design, promotes study of the design as a whole, which has been proven to improve overall costs, quality and time to market. However, many current commercially available CAD packages still tend to concentrate upon 'component-oriented' design, where individual parts are modelled and then assembled to create the final product. Hence, a need has been identified for development of an "assembly-oriented" CAD environment. As mentioned above, DFA claims proven success in reducing part count, improving product quality and minimising assembly problems. Therefore DFA, integrated within a CAD environment, has been established as a significant step for consideration of assembly issues.

One aspect of the DFA methodology [29] is an evaluation of the manufacturing processes required for each component of the product, based upon a subjective shape complexity analysis, reminiscent of part coding. However, as parts are integrated or eliminated to optimise assembly with respect to part count and assembly operations, inevitably more complex components are created and more complex insertion processes are required. The overall assessment requires that the time and cost of production is minimised, but this obviously requires a compromise between manufacturing overheads, assembly processes and part count.

This is where geometric reasoning comes in. In order to evaluate a product with respect to all these aspects of design it is important to consider complexity in many different ways. Ideally, the calculation of shape complexity should be automated using data extracted from the CAD model, to reduce subjectivity and enable a direct mapping between a component and its ideal method of manufacture. Furthermore, an appropriate classification scheme would also enable reuse of existing parts and the reduction of variance, both within the product and across a range of products, by making component comparisons possible. A measure of complexity for the assembly and product configuration should also be considered. The ultimate objective is to fulfil the product function by creating the 'simplest' design.

3.2 Role of Complexity Analyses

In order to find the optimum balance for a product design, between manufacturing capabilities and assembly operations, the notion of complexity will be considered at two levels: Component and Assembly.

A general layout of these two levels of complexity is shown in Figure 1.

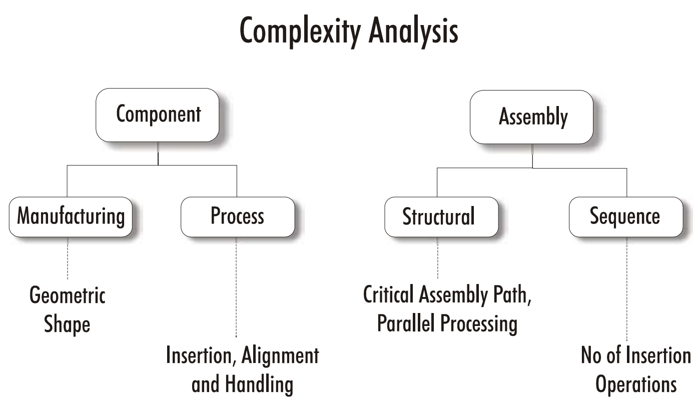

Figure 1. Different complexity factors considered at a particular level.

3.2.1 Component Complexity

Component complexity encompasses those aspects of the design that relate directly to each component and are not directly affected by the assembly sequence. These are:

Manufacturing Complexity, C_m – The type, number and difficulty of manufacturing operations is directly related to the geometry of a component. Some attempts have been made to automate the calculation of shape complexity, as previously discussed. However, the existing DFA methodology requires the designer to subjectively select a shape classification according to a global shape type (rotational, prismatic or thin-wall) and a complexity ranking based on the number and type of additional features. This is used to identify components with particularly inefficient or costly manufacture. As the number of parts is reduced to improve assembly, this can result in yet more complex components, requiring new materials and/or manufacturing methods. Care must be taken to ensure that the benefits of reduced part count are not outweighed by the cost of producing the new components.

Process Complexity, C_p – This notion of complexity is required to quantify the difficulty associated with alignment, insertion and handling operations on individual parts or subassemblies. Current DFA techniques provide a scoring system to evaluate these aspects of assembly and thus highlight components that present particular problems. Alleviation of these problems through redesign is often also beneficial in terms of manufacturing complexity.

3.2.2 Assembly Complexity

Assembly complexity encompasses those aspects of a design that affect the efficiency of the assembly sequence. These are:

Structural Complexity, C_{st} – The configuration of a product in terms of its product structure is not addressed by current DFA analyses, other than to eliminate non-functional parts wherever possible. However, the structural breakdown can have a great impact on the ease of assembly, but more particularly on the critical assembly path. Subassemblies within a product structure enable parallel processing on the shop floor and provide more flexibility for production scheduling. Proper consideration of such issues also enables use of modular design techniques in some industries. However, a hierarchy that is too 'deep' generates increased part tracking, storage and inspection requirements. Part handling also becomes significantly more difficult since the interfaces between subassemblies require careful consideration to minimise problems when mating groups of parts.

Sequence Complexity, C_s – The number of operations required to assemble a product is directly influenced by decisions made at the design stage, but also by the assembly sequence chosen. The number of insertion operations is directly proportional to the number of components, but a badly defined assembly sequence may incorporate many unnecessary operations, such as turnovers, and necessitate additional tooling.

The aim of the research will be to minimise the overall complexity of the product by finding the optimum balance between these factors, and thereby ensure design of the most cost-effective solution in terms of manufacture and assembly.

4 THEORETICAL CONSIDERATIONS

Before trying to define specific metrics for complexity, we need to consider how the different types of complexity interact and identify the factors upon which they are dependent. Since there is no prototype that clearly supports our viewpoint, the next model is proposed as the foundation of our postulations.

In the first instance the following basic assumptions have been made:

- A large number of *simple* components yields a complex assembly and therefore a highly costly one.
- A small number of *complex* components also yields a complex assembly and once again is highly costly.

So, when is a model simple enough, yet part-count efficient? Figure 2 indicates how such a model may work.

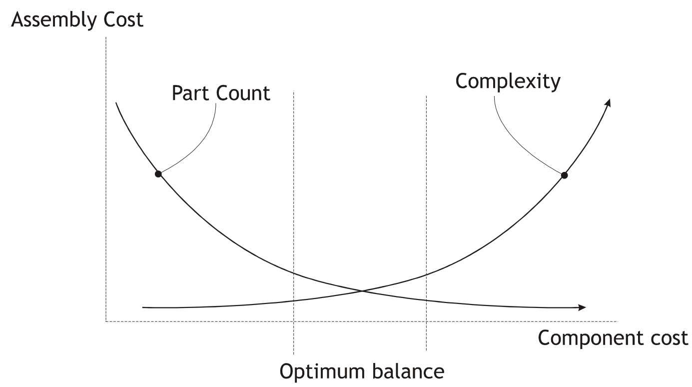

Figure 2. Influence of component complexity and part count on cost.

Implicit in these postulations is the fact that, regardless of the complexity of the individual components, the higher the number of parts the more complex the assembly. But this is not a continuous growth. The assembly would reach a point of complexity stagnation, as shown in Figure 3.

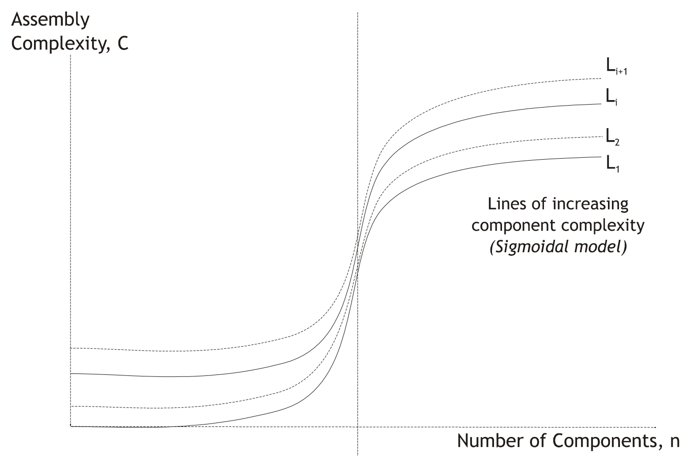

Figure 3. Total Assembly Complexity *vs.* Number of Components

For an average level of complexity of individual components, the "S-shaped" curve represents the expected behaviour of the assembly complexity for any given component complexity. The hypothesis of such behaviour could be modelled using *sigmoidal models*, that is, distributions such as *Gompertz, Logistic, Richards, MMF* or *Weibull*. The inflection point would represent a saturation of the assembly complexity, in other words, the complexity of that particular assembly would grow according to the number of parts in the construction, then after the saturation point - regardless of the number of components - the assembly would tend to present a stable behaviour, perhaps a state of periodicity in which the components present a specific complexity such that the assembly itself might be unaffected and even predictable no matter how many parts be added afterwards.

These assumptions are in accordance with the models of complexity reviewed earlier on, particularly that of Tang [2].

Several factors that will influence product complexity have also been identified. Taking each type of complexity in turn, the research will explore the relationships between the various elements. As a foundation, the following postulations have been made:

- C_m = f (geometry, material, tooling, process, batch size),
- C_p = f (geometry),
- C_{st} = f (n, levels in hierarchy, number of subassemblies, max number of components/ subassembly or number of branches or precedence levels),
- C_s = f (n, number of assembly operations),

In addition, the overall design complexity can be considered as a combination of the different types of complexity. The following model is proposed (*Equation 1*), where C_T represents the total complexity. The research will attempt to define a threshold value for C_T above which redesign should be considered.

$$C_T = \frac{w_1C_m + w_2C_p + w_3C_{st} + w_4C_s}{w_1 + w_2 + w_3 + w_4} \qquad (1)$$

Since the different elements of complexity are often in conflict, the optimum balance must be found. The number of components is a major factor affecting many aspects of complexity and thus provides the key to compromise. Once a model for the behaviour has been established then the optimum number of components may be found as follows in Equation 2.

$$\frac{dC_T}{dn} = \frac{d}{dn}\left(\frac{w_1C_m + w_2C_p + w_3C_{st} + w_4C_s}{w_1 + w_2 + w_3 + w_4}\right) = 0 \qquad (2)$$

The ultimate objective for the research is the formulation of differential equations to represent the intricate relationships that exist in the model. Yet, at this early stage, some ideas can be considered of particular interest. Geometry seems to be a common factor in most of the types of complexity. Therefore a suitable computational implementation of the model requires the exploration and analysis of any available geometric data.

5 SANDPIT REQUIREMENTS

Since shape complexity affects both manufacturing processes and the feasibility and intricacy of assembly operations it is a fundamental aspect of the research in the Designers' Sandpit environment and will be addressed first. Thus algorithms to calculate the shape complexity of the different parts that constitute the assembly will be derived.

The classification of shape is important in many aspects of engineering. It is often useful to group parts by their required manufacturing processes or common features, as addressed by group technology codes. However, shape complexity is also a major factor in the determination of component manufacturing difficulty and associated costs, as previously discussed in Section 3.2.1.

Examining the DFA manufacturing analysis in more detail we see that, components are divided into three main types [29]:

- *A parts* – the part envelope is largely a solid of revolution;
- *B parts* – the part envelope is largely a rectangular or cubic prism;
- *C parts* – flat or thin wall section components.

Within these categories, components are then ranked on a scale of 1 to 5 according to the number and types of features and the complexity of the surfaces. These 'definitions' of shape complexity illustrate the vague and subjective nature of shape classification in general, and thus highlight the difficulties in automating the DFA procedures. In order to create a useful computer-based tool for DFA analyses, the definitions of shape complexity must therefore be adapted to create a measurable and objective system of classification.

As stated later on, shape complexity is a fundamental aspect of research and will be addressed first.

6 RESEARCH AGENDA

The objective of the research is to model complexity for support of design decisions. Therefore it is necessary to:

- Establish precise definitions for each type of complexity.
- Define units of measurement (e.g. assembly 'entropy' or MTM values for manufacturing and assembly operations)
- Determine weighting of different factors to define an overall complexity, C_T, for a product and develop metrics to compare different types of complexity (e.g. ratios).
- Identify hidden dependencies (e.g. component gripping is dependent upon the assembly sequence because some surfaces may not be available).

6.1 Shape Complexity Quantification

Shape complexity can be determined for each component, but for a better understanding of their combined effect in an assembly, this must be calculated such that it may:

- Be used in conjunction with other metrics,
- Be combined in calculation of configuration complexity,
- Enable comparison of shape similarity (for reduction of variance).

One approach is to consider complexity in terms of a hierarchy, where measurements can include the number of levels (depth) or branches (breadth). Consider such a tree structure in relation to component topology: The top level (root) is the CAD model as originally presented. Subsequent levels represent the object obtained by iteratively stripping the model of its features. When the simplest shape (primitive) has been achieved, then the numbers of levels traversed will be one measure of component complexity. The number of features identified at each stage will define the breadth of the tree and will be another measure of the component complexity. The primitive and features obtained at each stage could also be used to identify similar objects.

Inevitably, the problem is not so straightforward: some types of surface are more complex than others and require more difficult manufacturing processes. For instance, doubly curved surfaces may be considered more 'complex' than planar ones since they often require dedicated tooling. Therefore some extra 'weights' must be added to the complexity measurement to account for this. Defining the precise geometric reasoning methodology and additional factors will form the basis of the research.

7 CONCLUSIONS

The paper has presented a detailed justification for complexity analyses in product design, both in terms of component considerations and assembly. The different interpretations of complexity that are relevant in this context have been described. Thus far, no existing work for the calculation of complexity has been found which will support the requirements of assembly-oriented design as defined in the Designers' Sandpit. The problem remains the creation of methods and metrics for assessing the impact of design decisions on production such that the most efficient product is designed in the first instance. In particular, the challenges for research are to identify all factors affecting the complexity of a design, and their interdependencies, and appropriate units of measurement to enable comparison of conflicting elements.

Above all, a geometric reasoning algorithm for shape complexity, which can also be used in conjunction with other metrics for the calculation of structural complexity, is a fundamental part of the work, and it will be addressed first as an appraisal of the fundamental purpose of the manufacturing analysis.

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