DIMENSIONS OF PRODUCT COMPLEXITY FROM DESIGNERS' PERSPECTIVES

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ABSTRACT

The perceived complexity of a product (product complexity) is doubtless an influential phenomenon in a design project. Insight into this factor and how it can be measured, is key to understanding its influence, supporting project planning and resource demand estimation. Opinions on product complexity vary greatly, with many definitions, scales and techniques to measure product complexity available; many of which draw their conclusions from engineering design research. Yet the field of product (or industrial) design companies, whose designers work across a vast range of product types, from domestic to industrial remains under researched. These designers have a tacit understanding of many influences over their projects, of which product complexity is one.

This paper presents an analysis of the dimensions (or measures) of product complexity found in literature and compares its findings to the measures defined by practicing product designers. This paper will demonstrate the process used to identify these dimensions and the scales developed to assess product complexity in a practical way and will make conclusions on the perspectives held on product complexity by product designers.

Keywords: New product development, Complexity, Industrial design, Product Complexity

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1 INTRODUCTION

Of the plethora of factors which can influence the resource demands of a product design project, the anticipated complexity of the product, referred to in this paper as "product complexity" is widely regarded as one of the most influential. There have been many definitions, scales, and techniques to measure this factor, within the engineering and design management disciplines, with an understanding that if it can be measured, or at least its scale can be understood, then a more accurate plan for a design project can be made. The higher the quality and accuracy of a project plan (a notoriously challenging task (Salam and Bhuiyan, 2016)), the greater likelihood of project success. Yet this is one area of design management that has been under-researched at a broader level. Many studies have been conducted into particular use cases, but little study has been made into the planning of design projects in a product design company (consultancy, agency, etc.) environment. Whether this is due to a lack of funding available, or lack of available time to conduct research, product design companies, and design-intensive businesses in general, provide a vital contribution to a country's economy. In the UK alone, design-intensive businesses contribute £97.4billion in gross value add and employ 1.97 million people (Hay et al., 2022).These businesses, including product design companies (PDCs), which are overwhelmingly SMEs, undertake many projects, all different in scope, market and, of course, complexity.

This paper presents an analysis of the dimensions (or measures) of product complexity found in the engineering design literature as well as product design to gather examples from a larger body of research (owing in no small part to the greater degree of investment). Comparisons are made between these found measures those found by practicing product designers. This paper will demonstrate the process used to identify these dimensions and the scales developed to assess product complexity in a practical way and will make conclusions on the perspectives held on product complexity by product designers.

2 PRODUCT COMPLEXITY IN DESIGN

The design process is complex. It has many inter-dependent procedures and the iterative design activities intrinsic to the process (Eppinger et al., 1994; Whitney, 1990) and is often characterised as complex, caused by an extensive network of interactive, diverse units that must come together to meet the common objective of a single product design (De Lessio, 2016). Further adding to the complexity, is the issue that the same problem may generate, or allow for a variety of different solutions (Harfield, 2007). This review considers product design as the discipline of developing physical artifacts and objects, is distinct from software-based design activities, and includes industrial design, design engineering and similar.

2.1 Measuring product complexity

By defining the characteristics of product complexity, attention can be given to the measurement of them as a means of measuring product complexity itself. If measures of complexity are agreed, then it would be possible for designers to identify risks to project cost, risks to project scope and risks and project schedule; as well as select alternative structures to avoid unnecessary complexity (Ameri et al., 2008; Hölttä and Otto, 2005; Phukan et al., 2005; Summers and Shah, 2003). Fundamentally, it is possible to minimise the design efforts of a team if a measure for complexity can be defined and used (El-Haik and Yang, 1999).

There are many measures of product complexity found in literature, shown in Table 1, which outline the measures defined through categorisation, examples of terms used by source and the sources themselves. Hubka and Eder (1988) define four levels of complexity for a technical system (the output of design activity). Ultimately, this is a single-dimension measure of complexity, based on the number of parts and subassemblies within a system, but many other sources consider many more. Simon (1996), Moran and Carrol (1996) considers the number of these parts and interconnectivity between them, whereas the number of parts becomes one contributing element to the dimension of size and coupling, as discussed by Ameri et al. (2008). In her doctoral thesis on the measurement of complexity in product development, Xiao Qi Zhang (2017) proposes a knowledge-based scale to measure complexity to evaluate the complexity of individual functions and integration tasks, where the intensity and diversity of knowledge requirements are incorporated.

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Table 1. Dimensions of product complexity in product design in literature

Measure	Example of text	Source	Number of Instances	Number of sources	Percentage of Measures
Functionality	Function, technology involved, integrated software, etc.	Bashir and Thomson (1999), Bashir and Thomson (2004), Bolañosa and Barbalhob (2021), Danilovic and Browning (2007), Danilovic and Browning (2007), Gonzalez et al. (2020), Griffin (1997), Hobday (1998), Hobday (1998), Hubka and Eder (2012), Kannapan (1995), Kota and Ward (1990), Kusiak and Szczerbicki (1992), Lindemann et al. (2009), Mauer (2017), Maurer & Lindemann (2007), Meyer and Utterback (1995), Pugh (1991), Shafiee et al. (2019), Shah and Runger (2013) , Shou et al. (2017), Shou et al. (2017), Tatikonda and Rosenthal (2000), Wang et al. (2021), Weber (2005), Xu and Yan (2006), Yoon et al. (2022), Zirger and Hartley (1994),	33	27	43.5%
Components	Type of, Number of, Interactions/Interdependencies between, etc.	Bashir and Thomson (1999), Bashir and Thomson (2004), Bolañosa and Barbalhob (2021), Danilovic and Browning (2007), Gonzalez et al. (2020), Griffin (1997), Hobday (1998), Hubka and Eder (2012), Kannapan (1995), Kota and Ward (1990), Kusiak and Szczerbicki (1992), Lindemann et al. (2009), Mauer (2017), Meyer and Utterback (1995), Pugh (1991), Shafiee et al. (2019), Shah and Runger (2013) , Shou et al. (2017), Ssah and Runger (2013), Tatikonda and Rosenthal (2000), Wang et al. (2021), Weber (2005), Weber (2005), Xu and Yan (2006), Yoon et al. (2022), Zirger and Hartley (1994),	24	13	21.0%
Creativity*	Skills required, Effort to design, Disciplines used, etc.	Ahmadinejad and Afshar (2011), Barbalho et al. (2019), Bolañosa and Barbalhob (2021), Frenken (2006), Mauer (2017), Novak and Eppinger (2001), Pugh (1991), Pugh (1991), Shah and Runger (2013) , Wang et al. (2021), Weber (2005)	7	7	11.3%
Form	Size, Shape, Structure, Architecture, etc.	Henning et al (2022), Hobday (1998), Xu and Yan (2006)	6	3	4.8%
Regulation	Regulatory intensity, Quality requirements	Hobday (1998), Mauer (2017)	4	3	4.8%
Manuf. & Assembly	Assembly complexity, Manufacturing difficulty, etc.	Alkan (2019), Hobday (1998), Shou et al. (2017), Ssah and Runger (2013)	5	5	8.1%
Financial	Unit cost, financial scale	Hobday (1998), Ssah and Runger (2013)	3	3	4.8%
Materials	Number of materials	Shou et al. (2017)	1	1	1.6%
			83	62	

Table 1 presents a non-exhaustive list of the dimensions of complexity found in design (specifically engineering and similar) literature. These dimensions can be measured and act as a quasi-measure for product complexity. One challenge found when reviewing these sources is the blur between dimensions that are explicitly product-related (those that describe a characteristic, feature, etc. of the intended product to be designed) and those which are organisational, environmental, or similar. Discussion of specific stakeholders involved in a project within the literature (Hobday, 1998; Lloyd, 2001; Moulianitis et al., 2004; Shah and Runger, 2013; Summers and Shah, 2003; Weber, 2005; Zhang and Luo, 2007) is broad and clearly influential over design projects. Yet these are also clearly a project-centric issues. Yet, there are dimensions that are not as clear cut. The creativity required to solve a design problem is one that is well regarded within the literature, (Ahmadinejad and Afshar, 2011; Barbalho et al., 2019; Bolaños and Barbalho, 2021; Frenken, 2006; Maurer, 2017; Novak and

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Eppinger, 2001; Pugh, 1991; Wang et al., 2021; Weber, 2005) and relates directly to the features of the intended design. However, this is viewed in the context of the abilities of design teams. Is this a true dimension of product complexity? These dimensions have been included in Table 1, although whether they belong on the list is still subject to debate.

What is shown in this literature, is that although there is some agreement between studies, as to the measure of product complexity, yet there is clearly still a high degree of disagreement as to what dimensions contribute to product complexity, as reflected in the right-hand columns of Table 1. Furthermore, this review does lend credence to the need for discussion on product complexity, as the topic with some regularity since 1991. This review posits a further question, how does one measure these dimensions of product complexity? Many of the sources reviews had their own suggestions, an analysis of which is too broad for the scope of this paper, including a simple numerical count, or scaled levels, like those shown in Hubka and Eder (1988).

3 PERSPECTIVES OF PRODUCT COMPLEXITY IN PRODUCT DESIGN COMPANIES

This section will present the findings of two case studies, conducted with UK-based product design companies. The first product design company has experience in developing products in a diverse range of fields, referred as Product Design Company 1 (PDC1). PDC1 has a team of six designers and a Studio Manager, all with varied levels of experience in industry and with degrees in Product Design Engineering or Product Design. This study is comprised of four workshops, all of which were conducted in the offices of PDC1. The number of participants included in each workshop was determined by the types of data gathered, with initial background information (design process, resource types, etc.) and estimation tool evaluation only requiring participation with the company director and office manager.

The second product design company has experience in developing and building small batch and bespoke products for a range of clients, working predominantly with natural materials, such as wood and leather. This consultancy, referred to as Product Design Company 2 (PDC2) has a team of two company directors (who act as the designers) and three manufacturing staff, all with varied levels of experience in industry and with varying qualifications and experience in architecture, design and manufacture.

3.1 Case study process

The case studies were conducted in at the studios of each PDC as part of a larger study to identify the factors that have the greatest influence over design effort demands in product design projects. The employees of each PDC (referred to as the participants) were gathered to participate in collaborative brainstorming activities, with the researcher acting as a facilitator. The participants were instructed to consider each phase of their design process and to consider what measures of product complexity would have influence over the design effort demands of their projects. The results of these were then collated with duplicates identified. These dimensions were then grouped into similar areas (like those presented in Table 1), from which, assessment criteria for these dimensions were developed as a means of measuring as either a four-point scale, or a binary (yes/no) question. Guidance was given to the participants that each level of the scales should be distinguished clearly and easily. The aim of this was to create a scheme for product complexity characterisation, similar to that provided by Hubka & Eder (1988). The terminologies presented within these studies are those used by the participants, representing the language of these organisations. Similarly, the groupings of each term identified within each case study is left as defined by each group. The intention of this approach was to capture how PDC design teams perceive these issues and therefore a prescribed grouping approach may alter how this perception.

3.2 Case Study Results

3.2.1 Product Design Consultancy 1 (PDC1)

The participants of PDC1 identified nine dimensions for product complexity when considering each phase of a project individually, shown in left of Figure 1. During the dimension grouping activity, the participants identified some refinements to the chosen list, with the combination of some dimensions, and the expansion of others, shown in Figure 1.

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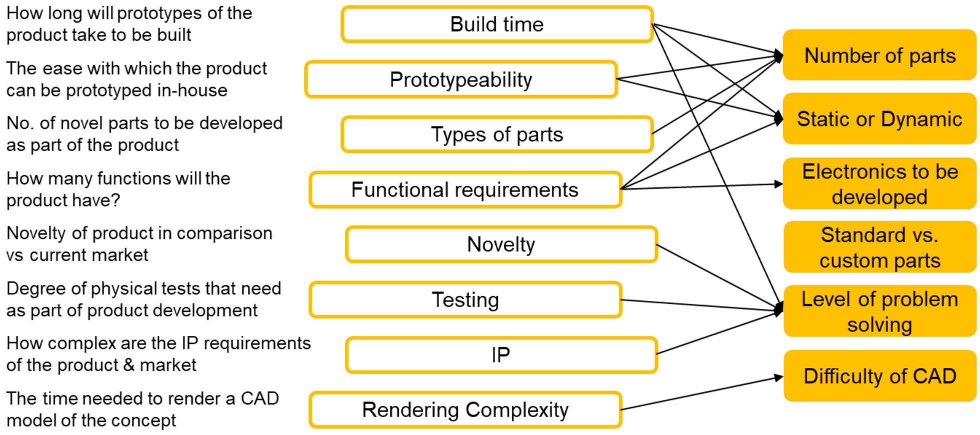

Figure 1. Dimensions grouping PDC1

Using the grouped dimensions, the participants collaboratively developed scales of measure for each dimension. Although given the option to have binary (yes/no, or similar) scales, the PDC1 participants opted exclusively for a four-point scale, shown in Table 2. Table 2 includes a point assignment for each level of the scale, so that an summative overall score for product complexity (PC) can be assigned.

Table 2. Dimensions and scales of measure for product complexity (PDC1)

Dimension	1	2	3	4
Number of parts	1	Up to 5	Up to 30	30 +
Static or Dynamic	Fixed	Fixed with some moving parts	Fixed with lots of moving parts	Moving with lots of moving parts
Electronics to be developed	None	Yes, no UI/UX	Yes, UI/UX (buttons & screen)	Yes, UI/UX, sensors control etc.
Level of problem solving	None	Basic	Medium	Complex
Standard VS Custom parts	All standard	Most standard	Most Custom	All Custom
Difficulty of CAD	1	2	3	4
PC Score Range	I (6 to 10)	II (11 to 15)	III (16 to 20)	IV (20 to 24)

3.2.2 *Product design consultancy 2 (PDC2)*

The participants of PDC2 identified nine dimensions for product complexity when considering each phase of a project individually, shown in Table 5, along with their definitions. As with Case Study 1, during the dimension grouping activity, the participants identified some refinements to the chosen list, with the combination of some dimensions, and the expansion of others, shown in Figure 2. Scales of measure were collaboratively developed by the participants from the grouped and refined dimensions. Like Case Study 1, PDC2 participants opted to use four-point scale measures for all their dimensions, shown in Table 3.

4 ANALYSIS AND DISCUSSION

4.1 Analysis of the dimensions of product complexity

This section will discuss the dimensions identified by the participants of PDC1 and PDC2 and will attempt to contextualise them based on the definitions developed in the literature review in Table 1.

PDC1 - Electronics to be developed

Whether the product will require electronic components to be included. This ranges from a complete absence of any electronic part, to one that has a user interface and user experience, with sensors, controllers, etc. PDC1 participants stated that the more electronics a product requires the more time it will take to develop the product. Electronics fall under the broader term of technology of which there have been many inclusions within the "Functionality" dimension in Table 1 (Danilovic and Browning,

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2007; Lindemann et al., 2009; Maurer and Lindemann, 2007; Meyer and Utterback, 1995; Tatikonda and Rosenthal, 2000; Yoon et al., 2022).

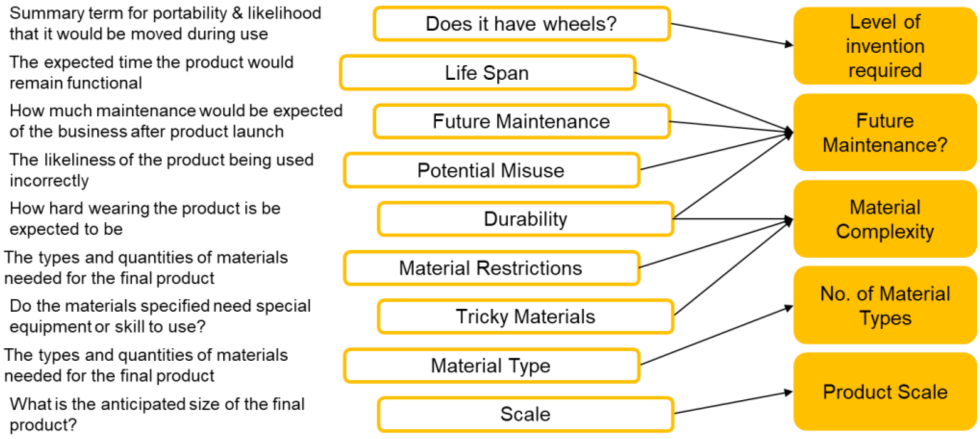

Figure 2. Dimensions Grouping PDC2

PDC1 - Static or Dynamic

The anticipated level of motion a product will have. This ranges from a fixed, stationary product, to a moving product with moving parts. Participants stated, the greater the level of motion, the more time will be required to design the product. This broadly aligns with "type of dynamics" and "Amount of possible states" defined by Mauer (2017), included within the "functionality" dimension.

Table 3. Dimensions and scales of measure for product complexity (PDC1)

Dimension	1	2	3	4
Level of invention required	Minimal	Average	Lots	WHAT?!
Future maintenance	Low risk	Average	High	Required / Anticipated
Material complexity	Easy	Hard	Very Difficult	WHAT?!
Product scale	Toaster	Microwave	Fridge	Rent-a-van
No. of material types	1	2	3	4+
PC Score Range	I (5 to 8)	II (9 to 12)	III (13 to 16)	IV (17 to 20)

PDC1 - Level of problem solving

The anticipated degree of mental challenges presented by the project, including but not limited to the need for complex movements, power systems, etc. to overcoming a particular set of functional requirements that are not complimentary. Problem solving is a variety of "creativity", with Summers and Shah (2003) and Lloyd (2001) stating problem solving as a dimension.

PDC1 - Standard vs. Custom Parts

The number of parts which require design effort to produce. This ranges from a product in which all parts are already available from suppliers to a product where the components must be designed by PDC1. PDC1 participants stated that as the number of parts to be designed increases, design effort needs increases. Within the literature reviewed and shown in Table 1, no specific source considers a ratio between standard and custom parts, yet with 24 separate dimensions from 13 sources discussing components, or parts, this can clearly be categorized as a "Components" dimension.

PDC1 - Difficulty of CAD

The perceived difficulty involved in producing CAD models, etc. for the product. This will relate to various elements, including the complexity of the product's form, the number of parts, etc. According PDC1 participants, the higher the perceived difficulty in producing CAD files for a product, the more time will be required to produce them. This relates to the "product shape" dimension defined by Xu and Yan (2006), falling under the "Form" categorisation. Yet this can also be considered a "creativity" dimension, as a challenging form will require more creative design effort (Shah and Runger, 2013).

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PDC1 - Number of Parts

The anticipated number of parts (NOP) the product will have ranging from a single part, to over 30. Participants stated that as NOP increased, the anticipated degree of product complexity would also increase. This shares clear links with the "components" dimension, with agreement found in literature.

PDC2 - Future maintenance

The lifespan of the product and the likelihood that PDC2 would have to perform care or other maintenance steps after the product was deployed. One of the likely triggers for maintenance would be its use and location in which it was used, which can increase wear and tear. PDC2 participants suggested that, although product complexity can be seen to influence maintenance requirements, they stated that more time would be spent in the development of the product if there was an anticipated increase in maintenance needs. Based on the definition provided by the PDC2 participants, this dimension may fall under "Functionality" or "Manufacturing" categories, with no specific dimension found in literature.

PDC2 - Level of invention required

Considers how much development would be required to create mechanisms, etc. as part of the overall product. PDC2 participants stated that the higher the level of invention required, the more complex the product would be. This, like "Level of problem solving" has clear links to the "Creativity" dimension.

PDC 2 - Material Complexity

The complexity of handling the material. This includes its fragility, as well as the difficulty of its use. PDC2 participants suggested that as material complexity increases, as too does product complexity. This is a clear dimension which would fall under the "Materials" dimension categorisation.

PDC 2 - Product Scale

The size of the product, was regarded by the PDC2 participants as influential over product complexity, increasing with size. The dimensions of "size" were identified by Xu and Yan (2007) and Henning et al. (2021) and included as part of the "Form" dimension.

PDC 2 - Number of Material Types

The anticipated number of different materials likely to be used in the final product. This ranges from a single material, through to over 4. PDC2 participants believe there is a direct correlation between the number of materials to be used increased, and the anticipated degree of product complexity, falling into the "Materials" dimension.

4.2 Discussion

There is an unusual dichotomy shown in the results from PDC2. Unlike PDC1, PDC2 prototype and manufacture many of their designs in-house, with members of their design team acting as makers also. This will narrow the range of projects PDC2 undertakes, which may influence the types of dimensions considered. This may also suggest the greater focus on manufacturing and materials-related dimensions ("material complexity" and "number of materials"), as shown in Figure 3. These are practical issues which they must face. This contrasts with the more whimsical or colloquial in nature of the levels they assigned to their scale, which seem less practical, in comparison to those of PDC1. Such whimsey may perhaps come from the vocational backgrounds of PDC2 team members, rather than the engineering/technical backgrounds of the PDC1 team. PDC1's dimensions have a closer alignment to those found in the literature, PDC1's dimensions have a greater focus on parts and functionality, issues that are generally considered at earlier stages of the design process.

Additionally Figure 3 illustrates that are clear differences in emphasis between literature and case study PDCs. The literature presents a clear focus towards a single dimension category, with functionality dimensions comprising of almost half of all instances found (43.5%). Whereas the distribution of categories is more even in case study data, with two sets of equal percentages (creativity and functionality at 23.1%, and form and components at 15.4%). However this even distribution is itself more focused, with no mention of regulation or financial-related dimensions from either participants. This discrepancy may indicate a lack of understanding of PDC practices by the literature but may also be influenced by the sources of data that each literature piece derives its

findings from. As the literature on PDCs is profoundly limited, the review includes sources from the broader engineering category. Such studies may take their data from industry examples that content with different issues that PDCs do not face, and conversely may not consider issues found by PDCs to have any influence at all.
Enabling participants to define their own groupings has advantages and limitations. By applying this case study approach more broadly, it will be possible to capture the specific perspectives of PDCs, which provides a richer dataset to analyse. However, the lack of homogeneity in the data captured will present challenges for that analysis itself.

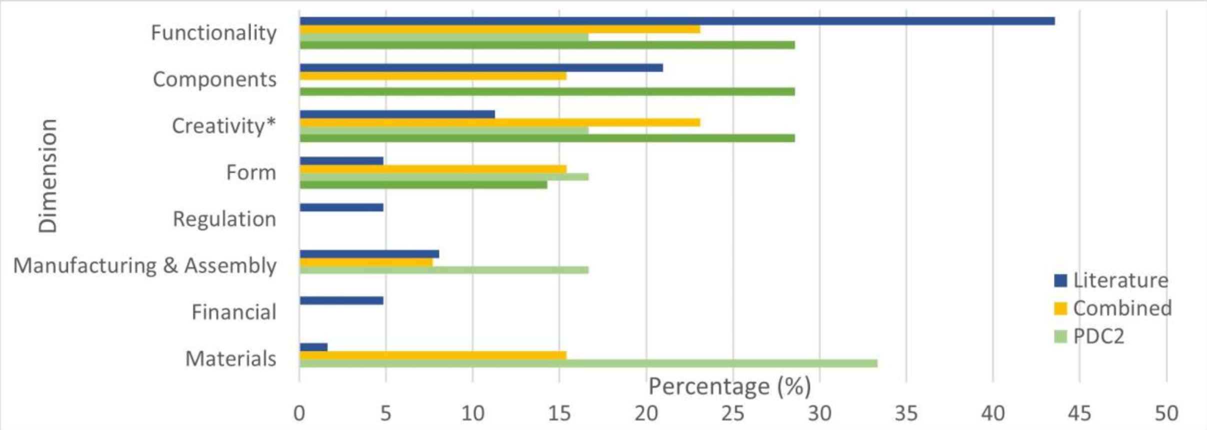

Figure 3. Dimensions of product complexity comparison (percentage)

5 CONCLUSION

Naturally, a study of two product design companies will not produce data that is reflective of an entire industry, far from it. Even with the "balancing" act of counting these measures and calculating a percentage (shown in Figure 3), a true industry-wide reflection cannot be gained. However, when compared to the findings of the literature review, it does indicate that different individuals and organisations have differing perspectives and opinions on what makes a product complex and how it could, and should, be measured. Logically practicing designers and design teams will hold their own working perspectives on many influential factors, based on their tacit knowledge and experience (Brauers and Weber, 1988; Eckert and Clarkson, 2010); Not least of all product complexity, as it is clearly the most significant influence over design effort (Holliman et al., 2020) and designers are required plan and estimate resources for new projects (Bashir and Thomson, 1999a; Bischof et al., 2007).
By defining a measurable scale for product complexity, a factor with significant influence over design projects, PDCs can better understand the projects they have already completed and develop a clear assessment of future projects. With which, PDC teams can better plan their projects, reducing waste and more critically preventing underestimation in project planning, leading to reduced earnings. This can have a significant impact on PDC survivability, benefiting the industry and the economy in general. Furthermore, with greater and deeper insight into product complexity, effective coping or mitigating techniques can be developed to reduce the impact that product complexity has over project resource demands, improving efficiency and consequently survivability. Naturally this investigation is limited by the number of PDCs involved. A broader, industry-wide investigation would be needed to provide significant value, however the clear discrepancy between dimension category instance frequencies in literature and industry underscores the for such an investigation to be conducted.
This benefit can be further amplified if PDCs were to identify all potential various factors which can influence the required design effort needs of a project and develop measurable dimensions for them. Firstly, by maintaining this open scope, it is possible to identify all the other factors that have influence over design projects. More importantly, this broader brief allows for a potentially greater range of dimensions for product complexity, as perceived by practicing designers. A greater, industry-wide study and analysis of these factors would be needed to fully capture the perspectives on an entire industry.

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