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In search of a dialogue for manufacturing conformance

When precise geometry is paradoxically imprecise design intent

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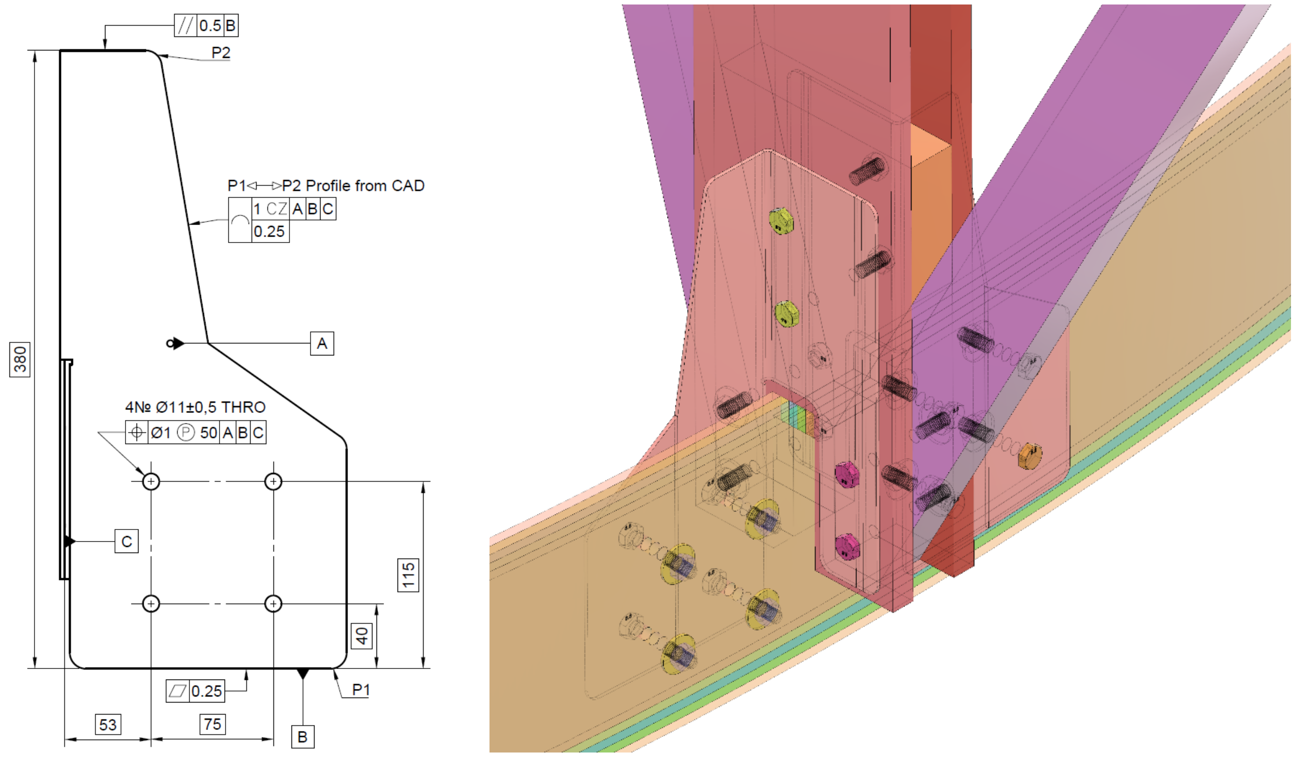

Fig. 1. *Study of Geometrical Product Specification (GPS) applied to the assembly of timber and modular sheet-metal parts by Bertie Hipkin, Arjun Bhakta, Qiren Lu, Yiming Lu, Chansokhan Nuon from the M.Arch in Design for Manufacture course (2019-2020) at the Bartlett UCL.*

1. Context

For anyone who has ever been to a construction site on a cold drizzly morning, stood on scaffolding to watch concrete being pumped into a muddy hole in the ground, it is a fair observation that construction is a challenging environment to control dimensional and geometric precision. As the VP of innovative technology at Trimble Inc., one of the World's leading companies providing positioning, modelling, connectivity and data analytics once commented: *"construction is messy ... and the digital twin is just not messy enough to capture reality"* [DCW, 2018].

Against the messy backdrop of reality on a construction site, analysts assessing the state of the Architecture Engineering and Construction (AEC) sector continue to report how digitally backward it is. That it fails to enjoy the same benefits from digitisation across its business processes when compared with almost all other areas of industrial activity and has barely improved its economic productivity over the last two and a half decades [McKinsey, 2015]. Many of the other major sectors surveyed such as Information and Communications Technology, advanced manufacturing including aerospace, automotive and defence have to an extent successfully adopted the practices and techniques that have been developed by industrialised manufacturing such as standardizing parts, part interchangeability, testing protocols for individual parts as well as assembly into modules and in particular continuous feedback from quality-control monitoring of process parameters.

In the UK context, it has been over twenty years since the UK Government's construction task force published "Re-thinking construction", a highly influential report that identified a range of challenges to the prevailing monumental conservatism and risk adversity that characterised much of the construction industry at the time. It proposed an ambitious list of recommendations and actions, amongst them standardisation, prefabrication and pre-assembly [paragraphs 58 to 64 in Egan, 1998]. In the contemporary global context, it is still anticipated that the largest potential for a shift in value pools will be the move into off-site construction in the order of (20 to 30) per cent of an estimated 265 billion USD in new and shifted profits [p. 12 in Ribeirinho et al., 2020].

The drive towards off-site construction is not solely incentivised by the prospect of increased economic productivity, there are anticipated improvements to quality control, fabric performance and safety, reduced

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waste, site rework, lead-in times and fewer disputes and delays to completion that together lead to a reduction in project risk [Gibb, 1999].

The AEC sector has been here before, as have systematic investigations of the challenges and detailed analysis of the opportunities in other industries that give grounds for optimism [Gann, 1996]. With so many potential benefits, evidence from the UK government of strong policy support for it [HMG, 2018], state-funded research and development towards improvement of the delivery, resilience and performance of infrastructure [CIH, 2019], there are reasons to be encouraged that progress will be made towards the large-scale adoption of off-site construction. Yet obstacles remain because while the desire exists and the outlook remains positive, actual progress towards improved productivity remains slow [Exhibit 3 in McKinsey, 2015].

Of the many differences that have been identified in the adoption of industrialised manufacturing techniques to produce a building project compared with an aircraft, car or mobile-phone handset, attention is drawn to the implications of one in particular: the demands that it places on the designer to produce a quality of information that best capitalises on its virtues. This is an information challenge for the manufacture of parts and their relationship within pre-assembled modules because the dimensional and geometric precision that is achievable in a factory can be and routinely are significantly higher than on a construction site [p. 196 in Gibb, 1999]. Supply-chains can be and often are geographically-distributed, including producing parts in isolation from their eventual pre-assembly into modules. These differences drive the quality of information needed to specify the control and coordination of the part's assembly interfaces if it is to make best use of each manufacturer's capabilities. By definition, off-site construction delivers pre-assembled modules to a construction site for installation at an even larger scale of dimensional variation.

2. THE PARADOX OF PRECISION IN REPRESENTING INTENT

State-of-the-art efforts are being made to introduce systematic tolerance management for the construction of whole buildings [Talebi et al., 2020] recognising the range of costly defects that the present lack of tolerance management is associated with [Talebi et al., 2016]. The importance attached to resolving the differences in dimensional variation between off-site construction and on-site installation to ensure fit so as to reduce rework and waste, is still seen as a challenge even at the level of national standards [p. 11 in Price, 2019]. The observation is that the information challenge to specify tolerance in the communication of design intent exists at two different scales between the designer and:

- Manufacturer with the requisite precision available at the point-of-production in a factory-environment for parts and pre-assembled modules
- Constructor with the requisite precision at the point-of-installation on-site of modules within the dimensional and geometric limits of site-built structures

Focussing on the former part-level and pre-assembled modules, the observation is that a manufacturer is better placed to test modules for conformance with tolerance requirements in a factory using systematic quality-control methods before it ever leaves the point-of-production compared with site-work. Once a non-conforming module has arrived on-site many of the advantages of this approach are eroded or lost altogether.

Herein lies one of the specific information challenges, while there is guidance for the specification of tolerance at the scale of buildings [BSI, 1990a], conformance with the requirement for construction elements to fit is still mostly defined by specifying a tolerance with linear dimensions for allowable size using values within a range. Product manufacturers, manufacturing machinery vendors, technical standards in contracts with fabrication shops have tended to offer guidance to designers in those terms, reflected in general information across for a wide range of materials and processes [Gulling, 2018]. Reference data for the dimensional variability of many building products, trades and construction assemblies already exists [Ballast, 2007] as do standards for guiding the structured collection of data for dimensional size *and* form at both the scale of parts from production lines as well as site-work from construction sites into machine-readable statistical distributions where references do not [BSI, 1990b].

To design for and manage the manufacture of parts and coordinate their assembly into modules, the digital perfection of geometry in a CAD file that can specify the coordinates for the location of a geometric feature on a part with 64-bit floating-point precision to six significant figures scaled to cm units [Autodesk, 2021] can paradoxically put the designer at a disadvantage. The central reason is that taken *prima facie* CAD geometry is a nominal representation of design intent while real materials, the fabrication processes that form them and assembly methods used to join, fix and fasten them into pre-assembled modules all either exhibit or impart dimensional and geometric variability. In teaching "design, making and measurement" as a pedagogy [Leung, 2020] "The death of determinism" inherent in this disparity is inescapable [Brandt, 2012]. The consequences are acutely felt when a designer is ill-equipped to either express or systematically reason about the implications of dimensional and geometric variability of a part with respect to its assembly, thus leaving manufacturers with little choice but to use it directly at the point-of-production [Chap. 6 in Davies, 2005].

A key contributing reason for this disparity is that using linear size tolerancing alone to express the functional requirements between mating surfaces on parts in assemblies can be ambiguous. A gauge designer working in the inspection department of a torpedo factory in Scotland during the 1930's can be thanked for providing key insights into why. Stanley Parker made physical test gauges to inspect the conformance of parts and assemblies manufactured from engineering drawings. His analysis of the problems inherent in a manufacturer's interpretation of a drawing's meaning in this context led to his development of a language for designers to precisely express intent and a system of ideas to standardize its interpretation by manufacturers to limit ambiguity [Parker, 1956]. Parker's work on position tolerance theory is credited with laying the foundations for the development of a framework of standards to specify geometrical dimensioning and tolerancing around the concept of “true-position” [Liggett, 1970].

Nearly one-hundred years later, practitioners in design, engineering, manufacturing production and inspection within the aerospace, automotive, medical and defence sectors world-wide use and continue to develop these standards [Humienny, 2009] in a bid to unambiguously express design intent for manufactures to interpret using the Geometrical Product Specification (GPS) framework [Henzold, 2006].

3. A DIALOGUE IN SEARCH OF A LANGUAGE

The challenges of adopting GPS as an information standard from engineering design to large-scale civil engineering and structures has been the subject of previous study [Milberg, 2006] as has its management for modular construction [Rausch, 2016]. The state-of-the-art in the literature for the construction industry has even proposed a dedicated language GD&TIC [Talebi et al., 2020]. The observation made here is that in each case the barrier to learning a new language is that it takes time, effort, training resources and perhaps most challenging of all the uncomfortable anticipation by participants in a dialogue using it that they will be provoked into a shift of thinking through the "adjustment" of long-held conventions and assumptions that had become reassuring habitual. In an information and contractual landscape as fragmented, conservative and risk adverse as the AEC sector has been diagnosed as suffering from in the past [Latham, 1994] this must be taken seriously as a barrier to acceptance even in contemporary highly digitally-literate practice.

Participants would be motivated that the investment is worthwhile if the prospect of common benefit through communication using it with those like-minded stakeholders willing to attain a corresponding level of literacy was sufficiently high. So what has industrialised manufacturing gained from adopting the GPS framework that could motivate the investment? The three most significant benefits claimed by the successful adoption of the GPS framework are [after p.6 in Bennich, 2005]:

- Lower manufacturing costs
- Larger manufacturing tolerances
- An unambiguous functional specification

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The reasoning is that removing ambiguity clarifies the priorities for where imprecision is tolerable, in which direction and by how much. The manufacturer who is best placed to exercise critical judgement can then decide *how* costly precision can be selectively projected only where it matters, and dialled back to less costly processes where it does not, and achieve this while in either case suffering *no* loss of functional performance. This clarity allows the logical reasoning about trade-offs in dimensional variability and geometric tolerance that are possible between the size, location, orientation and form of mating parts in assemblies, often resulting in a design that can accommodate a more generous tolerance zone for which a manufacturer can select a less costly process.

In coming to terms with the paradox of ambiguity in the apparent precision of geometric CAD input, a complete functional specification using the GPS framework applied to the geometric features of a part can then be used to help define thresholds for its conformance. This aids the metrologist to assess conformance with the functional specification. In industrial applied metrology for precision parts this is well-established as Model Based Definition (MBD) information embedded in a part's digital file that is both machine-readable and actionable by Computer-Numerically-Controlled (CNC) Coordinate Measurement Machines (CMM) to automate a conformance test [pp. 334-335 in Nobou, 2016]. Adapting these principles to the scale of pre-assembled modules and buildings this has the obvious potential to aid the resolution of disputes since there is a defined measurement that can be made to establish conformance *versus* non-conformance.

Each of these claims has its own appeal and taken together appears to make a compelling case, if this is a language to use in a dialogue for manufacturing conformance then which individuals within the construction team and along the AEC sector's supply-chains are best placed to become literate in, contribute to the dialogue and reap the benefits of its advantages when the collective goal is to create successful buildings? We might turn to the pre-digital past for inventive constructors who practiced directly at the point-of-production with intimate knowledge of specific material-to-manufacturing process interactions for an idea of the characteristics of the dialogue they had and the results that were built to show for it [Wigley, 2017], while providing a historical perspective to contemporary practice [pp. 82-88 in Albus, 2018] it highlights the challenges the AEC sector still faces. Veterans of Design for Manufacture and Assembly (DfMA) practice who have been evolving ever since the days of Egan's report into the contemporary platform-based approach to construction [BrydenWood, 2018] are among an increasing range of practitioners who straddle the cyber-physical boundary between design intent and producing machine readable, actionable information output and able to take feedback from applied metrology feature-extracting geometry from the manufactured output.

While analysis of the AEC sector's workforce demographic and the industry's labour model has put it on notice of a worsening skills-shortage [Farmer, 2016], it is argued here that there is also an "awareness shortage" in the AEC sector about these information standards that have long been established in industrialised manufacturing. As an educator, there is an opportunity to motivate perhaps the most digitally capable generation of students in history to become literate in the GPS framework as a contribution towards mastering the information challenges needed for successful off-site construction.

4. MANUFACTURING CONFORMANCE

The title of this keynote could be misconstrued as suggesting the dialogue being sought is the rather dull confirmation that a project's design somehow "conforms" by being manufactured at all. The contention is that if precise CAD geometry is ambiguous for manufacture then the dialogue being sought has the terms of reference for expressing design intent as a currency in a speculative trade for *possible* manufacturable outcomes. It is suggested that the desire for conformance in the outcome, whether by metrology to [BSI, 2017] and/or another metric in the trade-space of manufacturing capability is more about an appropriate means to calibrate the currency's value.

On this basis, the risk of deficiencies in the quality of a dialogue for manufacturing conformance is akin to an increase in the entropy of a physical system, as it increases the amount of useful work the system can make available decreases. The title of this keynote is intended to suggest that conformance itself is manufactured, as a by-product of success in the dialogue between the designer, maker and metrologist. Far from dull, not only is this a creative opportunity, it has the ingredients for inputs to design computation processes that can be defined and outputs from the process that contribute to improving off-site construction as outlined.

There are further cultural and discipline specific barriers that may need to be overcome to benefit from the advantages claimed by the adoption of GPS. It is offered as an anecdotal as well as professional observation that many designers of buildings tend to develop the setting-out geometry that describes a design in a single digital file with reference to a structural and planning grid, where for example on the outline of a building's envelope each intersection is located with linear T.E.D.s (Theoretically Exact Dimensions) coordinated to the (X, Y, Z) axes of the grid. Or a large-scale surface over a form, this might be characterized as a "top-down" approach. It is also an anecdotal as well as professional observation that many mechanical design engineers tend to develop the geometry of individual parts that constitute a design with reference to a datum system in each distributed part file that are brought together in an assembly file, this might be characterised as a "bottom-up" approach.

A key difference in the latter is that rather than coordinating each part to an abstract grid both the size and geometrical relationship of each part is coordinated by the functional requirement implied by the interface it has with another part or parts such as at their mating surface, slot, fastener hole or seam. The component-based assembly approach of the latter lends itself to the application of the GPS language and system-of-ideas simply because the relationship between components can be made explicit and evaluated systematically using the logic of the sequence in which the parts are assembled. It would arguably represent a significant cognitive shift for designers of buildings that are accustomed to a "top-down" approach working from the overall geometry or surface-based form to engage with the latter.

Further, a datum system is easier to implement conceptually as well as practically at the physical scale of a part or pre-assembled module in a factory environment than it is on the scale of a whole building on a construction-site. The repeatability and reproducibility of dimensional and geometric metrology on a construction site faces the challenge of more variable prevailing environmental conditions and ensuring the visibility and survivability of datum markers for a project such as retro-reflective targets, corner-prisms with respect to geo-located points in an official control system throughout a project's build time.

If a considered "Design for Metrology" [Morse, 2019] decision-making were invested into the placement or projection of control points at those interfaces where the requisite precision matters most [BSi, 1990c] such as for structural load-transfer, weather protection, air-tightness, fire-compartmentation or thermal continuity at the interfaces of fastener holes, along 2D profiles or 3D surfaces between mating parts in pre-assembled modules then physical gauges, optical distance markers, laser projected profiles [FARO, 2020] or inspector point-of-view AR (Augmented Reality) virtual gauging could be used to test parts for (GO) or (NOGO) conformance.

5. DISCUSSION

One might speculate that Stanley Parker's occupation as a gauge designer afforded him a vantage-point that spanned sufficiently far across the organisation's activities to identify ambiguities in design intent due to the drawing conventions used by engineers in his day, recognise the implications this held for the priorities given by manufacturing to selectively project precision onto features of a given part because of it, and ultimately the consequences that this had for measurement with the gauges he needed to make in order to inspect the part for its conformance with the design specification. The point being that he needed to be in the right place to see the problems in order to develop a language to express and devise a system of ideas to interpret how these might be overcome.

Whether or not there is any truth in this, the parallel drawn here is that in the search of a dialogue for manufacturing conformance the protagonists need to occupy a vantage-point from which to identify ambiguities implicit in design intent due to the CAD information

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practices of today, recognise the qualitative and quantitative implications this has for the manufacturing of parts and pre-assembly of modules at the point-of-production and ultimately the consequences this has for the measurability of the manufactured output for its conformance with the design specification in the first instance.

6. Conclusions

An experienced architect once advised me that the beginning, middle and end of an architect's ability to realise the building that they had agreed with a client was sometimes more dependent on the design of the contract used to administer the project than the design of the building itself at the time the contract was let. The reasoning was that without first establishing effective terms of reference for a team to engage in a fair and meaningful negotiation within quantifiable dimensions of quality, time and cost while maintaining safety to deliver the building's intended design, the outcome is compromised by weaknesses in the process itself regardless of the design intent's ambition, this view echoed [Egan, 1994].

In an effort to achieve parity with a fair and well-thought out form of contract, adopting the GPS framework could contribute towards systematic terms of reference for a meaningful dialogue between a designer expressing intent with less ambiguity communicated to the manufacturer whom could then exercise their creative selection and deployment of manufacturing processes to best effect onto materials and into parts and pre-assembled modules, while providing clear criteria for success for the metrologist to establish its conformance.

It might be tempting to seize the GPS framework for use as yet another jigsaw piece offered into the puzzle of tackling the huge challenges in the AEC sector, that it might be seen solely through the lens of fitting together with other parts driving toward greater efficiency and economic productivity within the terms of reference of existing unsustainably resource-intensive global trade and its contribution to anthropocentric impacts on the environment and climate. History reminds us of Jevon's paradox in the *prima facie* pursuit of efficiency in the engineering as well as economic sense of maximising throughput as a percentage of the labour, material resources and capital that is available [Polimeni, 2015].

The contention is that this would be a missed opportunity to cultivate the dialogue suggested here because an alternative view is that improvement to dimensional and geometrical representation for manufacturing and the metrology of its outcome could instead aid resource *efficacy*. Identifying the greatest need first and then provide the terms of reference to creatively match it with manufacturing capability and resource availability second, such that its use can be sustained in balance with the dynamics of that need within a calculus of resource resilience.

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