SYSTEMISATION OVER STANDARDISATION: A COMPUTATIONAL DESIGN APPROACH TO DIGITAL TRANSFORMATION WITHIN CIVIL INFRASTRUCTURE ENGINEERING, BIM, MODELLING AND DRAFTING

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ABSTRACT

Professional industries - including the architecture, engineering and construction (AEC) sectors - are undergoing a radical transformation. Spurred on by unprecedented advancements in hardware and applications of evolving software domains encompassing Artificial Intelligence, Machine Learning and Big Data. Effective digital transformation should not be characterised by digitisation of traditional workflows and methodologies. Instead, successful implementation of systematic, standardised, and interoperable workflows across geographical boundaries and time zones is a characteristic of the modern progressive, digital civil engineering discipline.

This paper demonstrates the application of integrated algorithmic design and encoding engineering knowledge and information - a necessary precursor for automation and implementation at scale. This paper uses two civil infrastructure topologies as case studies - one for a tunnelling project and the other for a multiple bridge design project. Both the design elements and impact of digitisation on the entire value chain of the discipline are emphasised. The emerging need for skills development (both traditional and evolving), revised scope definition and relevance of project deliverables is also considered.

The presented examples demonstrate the iterative evolution necessary to realise a coherent, digitised engineering design and delivery process, in tandem with the lessons learned from failures and inefficiencies. Realisation of a transformed engineering industry is predicated on the continuous investment in resources, technology, (re)training and skills development by all parties, individual organisation, private, and public.

1. INTRODUCTION

It is said that the best way to predict the future is to create it. Like the digital revolution at the turn of the millennium - marked by the widespread adoption and expansion of the internet - professional services and industries, including architecture, engineering, and construction (AEC) are undergoing a radical digital transformation. The present period of digital transformation, often referred to as "Industry 4.0", is the realisation of improved productivity, operational efficiency, and value-adding processes (Lu, 2017) through automation, optimisation, production customisation and digitisation (Roblek et al., 2016). The essence of digital transformation is not merely digitising old ways of working. Rather, successful digital transformation relies on a differentiated mindset open to new and different ways of working, reducing friction and unlocking capacity through fit-for-purpose technology.

Professional knowledge can be regarded as tacit in nature and is key to the competitiveness of an organisation (Enakrire & Smuts, 2023). Conversely, the imminent proliferation of Society 5.0 – a knowledge-intensive society where a balance must be struck between a system of social good and the cyber-physical space (Smuts & Van der Merwe, 2022) – introduces a duality to the dissemination of knowledge, accommodating both human and machine. This juxtaposition enables people to serve as both generalists and specialists; specialised to guard against the pitfall that technology is a panacea, but generalists to actively identify areas within an organisation that can benefit from mature, fit-for-purpose digital technologies.

1.1 Aim of Paper

This paper presents the interplay among concepts of knowledge substructure, integrated systemised design processes and incremental digital transformation. This underpins the actively changing methodology of operation (working) within the AEC industry. Furthermore, two case studies demonstrate the intuitive, intelligible, and uncomplicated process of systematising engineering knowledge into an interoperable data format. This improved flexibility stands in contrast to the existing software ecosystem characterised by a lack of interoperability and proprietary data formats.

These case studies exemplify the appeal of routine task automation, achieving a flexible and methodical implementation at much larger scales, and in turn guiding innovation toward systemisation rather than standardisation.

2. THEORETICAL BACKGROUND

2.1 Digital Ways of Working

The terms of digitisation, digitalisation and digital transformation have become fundamental concepts within the AEC professions, however, it is imperative to note the nuanced differences between the three stages (Verhoef et al., 2021):

1. **Digitisation** is simply the digitising process of information. This is analogous to creating engineering drawings using computer aided drawing software (CAD); replacing the pencil with a computer mouse.
2. **Digitalisation** is the act of increasing the level of automation in processes using digital technologies. Incorporating digital services such as centralised common data environments (CDEs), enables seamless integration between different disciplines.
3. **Digital transformation** is the novel use of digital technology to accelerate business strategy. It is about the application of digital technologies to empower people, optimise processes, and automate systems in the organisation to radically reorient its business performance.

The key activities behind a modern consulting engineering firm are related to the production of engineering calculations, drawings, designs and, more recently, Building Information Modelling (BIM) models, working with key partners in industry, academia, software vendors and industry risk partners. The absence of the prefix digital to these outputs is intentional. The incorporation of digitisation processes on its own does not constitute a digitally transformed business model. To be transformative reimagines how problems are approached, tacit knowledge disseminated, solved and delivered using a computational mindset. This is an iterative process where problems are decomposed into smaller parts, generalised to recognise patterns, algorithmically solve the problem one step at a time, conceptualise and explain solution and finally, evaluate, improve and debug.

Susskind & Susskind (2017) noted how the industrial revolution coincided with the development of professions with experts in the handling of large bodies of information and knowledge that were subject to regular change. A significant characteristic of current society is the use of a technology-based always connected internet. Machines are increasingly displacing tasks historically confined to specialised professions. Incremental digital transformation is a pertinent driving force (Fuchs & Hess, 2018). This is reflected within the AEC industry as a blended profession, often referred to as Computational Design (CoDe), evolving alongside digitised business operations (Cagan et al., 2005): a design and modelling methodology that makes use of an innovative combination of algorithmic thinking and parametrisation, used to solve design problems with advanced computer processing capabilities. The emergent CoDe profession speaks to an evolving *information substructure* – the dominant means by which individuals and organisations access specific kinds of expertise and knowledge. At the forefront of the modern, hyper-connected information substructure, new technologies and novel innovations are often disproportionately amplified; the Gartner Hype Cycle™ (Gartner, 2023) typifies a cycle through which these developments occur over time (Figure 1):

1. **The innovation trigger** associated with a technological breakthrough or when a product is launched to wide public acclaim.
2. **The peak of inflated expectations** is encountered when the hype disproportionally exceeds the usage or utility that an innovation or utility can provide.
3. **The trough of disillusionment** is post-peak as performance issues are reported combined with low return on investment.
4. **The slope of enlightenment** follows as early adopters see through the growing pains and adapt innovations for their organisation.
5. **The plateau of productivity** is reached with increasing, mainstream adoption of a more matured iteration of the innovation.

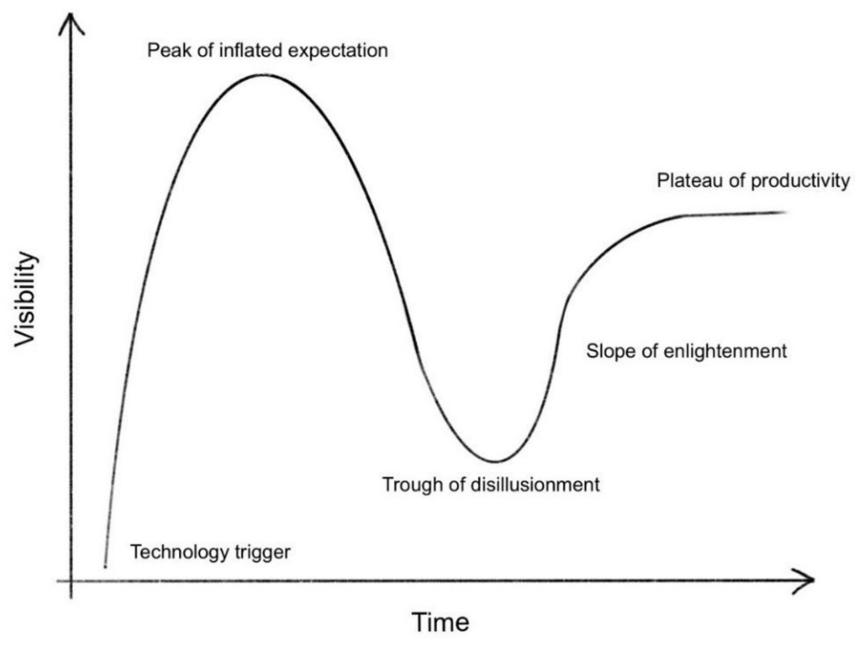


Figure 1: Typified Gartner Hype Cycle (adapted from Gartner, 2023)

2.2 The Integrated Systematised Design Process

As a result of the incremental innovation within information substructure, a hybrid skills model, often described as a "T-shaped" employee (Demirkan & Spohrer, 2018), has become very desirable within a professional AEC workplace. This hybrid worker is a depth of knowledge expert in at least one subject and skilled in several others (breadth of understanding) for transdisciplinary value addition (Bodell, 2020); they are both a specialist and a generalist. The demand for these skills severely exceeds a limited supply, with nearly 90% of executives confirming that their respective organisations either face, or expect to face, a skills gap within the next few years (McKinsey, 2020). A T-shaped skill set covers a range of interests, including engineering, architecture, mathematics, computer science and information management – a diverse portfolio. Typically an individual will have at least one formal qualification within one of these areas, with a keen interest in digital technologies. CoDe serves as a catalyst and support mechanism to craft and externalise a systematised information workflow (Wintour, 2022) necessary to realise the value-adding and automation potential characterised by Industry 4.0. Contextualised as an Integrated Systematised Design Process (ISDP) **(**Figure 2**)**. The ISDP aims to encapsulate the incremental development of a repeatable solution into a set of problems.

The ISDP represents the information substructure in the current societal period (information technology), preceded by the eras of orality, script and print. Its functionality is predicated in which manner practical expertise is created and shared, influenced by the systems that are available for its storage and communications. The information substructure not only strongly influences the way in which practical expertise is produced and distributed, but also determines the quantity of practical experience, its complexity, its source, its availability, the frequency with which it changes, and the human beings or other systems that can reliably apply it in its affairs (Susskind & Susskind, 2017).

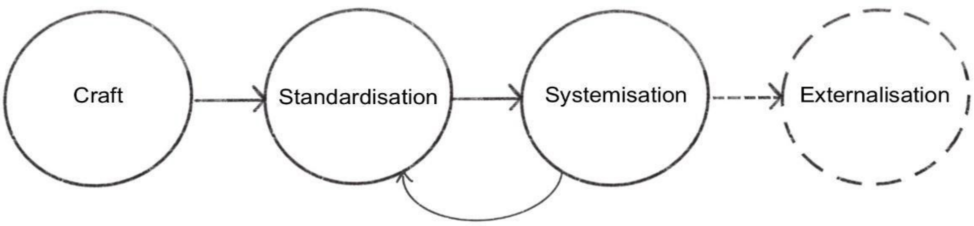


Figure 2: Graphical interpretation of an integrated systemised design process (ISDP)

1. **Craft**: Within the AEC environment, tools are tailored and customised for each project. Crafting, in practice, tends to be a marginal activity; a unique endeavour or solution. It should represent a very small portion of the overall output produced.
2. **Standardisation**: The renewed popularity of BIM prioritises standardisation, embedding tacit knowledge for reuse. Consistency is prioritised, with the aim of negating errors through the implementation of checklists, procedure manuals and standards.
3. **Systemisation**: Systems are developed to augment – not replace - the capabilities of experts. Where standardisation involves reducing tasks to reusable routines, systemisation involves codifying knowledge into a machine-consumable format. This results in improved validity and consistency of information.
4. **Externalisation**: Integrated tools and systems that have been developed to be predictably repeatable are made available to end users as an automated service. Users of these services have implicit trust that the process works and often need no understanding of each of the steps within the process.

3. METHODOLOGY

3.1 The ISDP Workflow

This paper uses two engineering design projects as case studies where digital transformation was evident. The ideation of an ISDP resulted from a strategic decision to intentionally codify the available tacit knowledge within the organisation, analogous to a digital transformation strategy (DTS) (Mapingire et al., 2022). This ISDP subsequently grew to capture a critical mass of CoDe tacit knowledge, representing the dominant approach to the delivery of these projects. Standardisation and systemisation within the ISDP were iteratively developed, allowing for selective automation and scaling as the project timeline progressed (Figure 3).

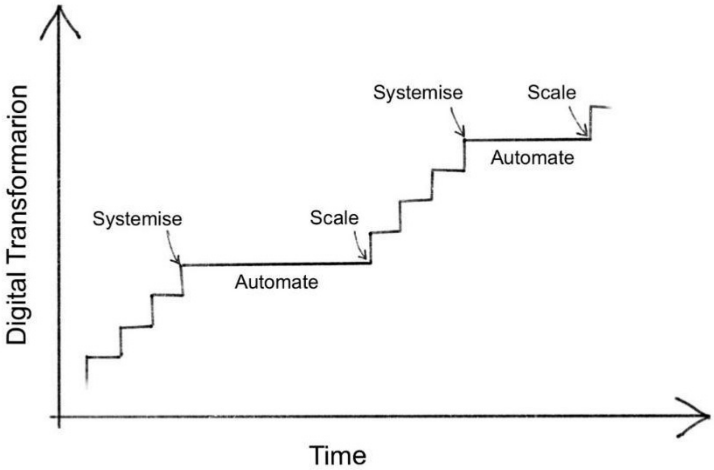


Figure 3: Incremental digital transformation over time

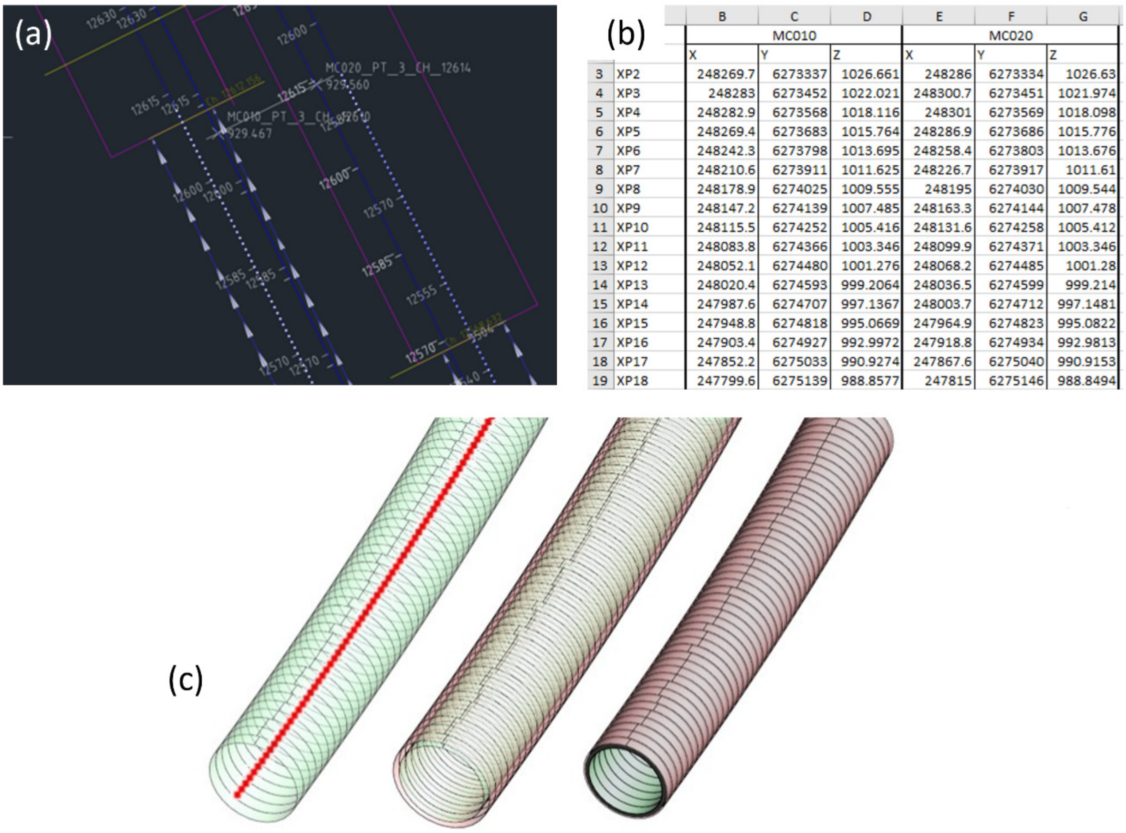
4. CASE STUDIES

4.1 The ISDP Workflow - Tunnels Case Study

The first case study makes use of innovative CoDe approaches for the modelling of an 11-kilometre dual carriageway bored tunnel (Figure 4). This approach is derived from the work of Ninic et al. (2020). The tunnel will be constructed using a Tunnel Boring Machine (TBM) which will install precast tunnel panels along the bored path. The tunnel structure also includes service tunnels and several cross passages.

The entire length of the dual-tunnel and its auxiliary structures were dynamically generated solely from data interactions, totalling over 30 000 model elements. Once the initial ISDP was developed, the modelling became a dynamically iterative process, unlocking capacity. The requirement to continuously iterate the route and cross-sectional details by the engineers for route optimisation was addressed. This demonstrates the applicability of the ISDP, allowing the digital delivery team the ability to develop, systematise and eventually automate in an ongoing capacity, sequentially benefiting from an incrementally transformed digital workflow (Figure 3). Based on the experience gained from the tunnelling project, the limitations of the use of rudimentary data systems (Figure 4b) were evident. In this instance, a CSV (Comma Separated Variable) file format. The limitation was dependent on the tacit, human understanding of the data's author – an information substructure with limited context of its genesis.

This led the authors to critically consider the data structure used within the workflow methodology. This depends not only on algorithmic thinking, but also methods of encoding interpreted data as well as the storage of said data for both human and machine readability and consumption.



		B	C	D	E	F	G
		MC010			MC020		
		X	Y	Z	X	Y	Z
3	XP2	248269.7	6273337	1026.661	248286	6273334	1026.63
4	XP3	248283	6273452	1022.021	248300.7	6273451	1021.974
5	XP4	248282.9	6273568	1018.116	248301	6273569	1018.098
6	XP5	248269.4	6273683	1015.764	248286.9	6273686	1015.776
7	XP6	248242.3	6273798	1013.695	248258.4	6273803	1013.676
8	XP7	248210.6	6273911	1011.625	248226.7	6273917	1011.61
9	XP8	248178.9	6274025	1009.555	248195	6274030	1009.544
10	XP9	248147.2	6274139	1007.485	248163.3	6274144	1007.478
11	XP10	248115.5	6274252	1005.416	248131.6	6274258	1005.412
12	XP11	248083.8	6274366	1003.346	248099.9	6274371	1003.346
13	XP12	248052.1	6274480	1001.276	248068.2	6274485	1001.28
14	XP13	248020.4	6274593	999.2064	248036.5	6274599	999.214
15	XP14	247987.6	6274707	997.1367	248003.7	6274712	997.1481
16	XP15	247948.8	6274818	995.0669	247964.9	6274823	995.0822
17	XP16	247903.4	6274927	992.9972	247918.8	6274934	992.9813
18	XP17	247852.2	6275033	990.9274	247867.6	6275040	990.9153
19	XP18	247799.6	6275139	988.8577	247815	6275146	988.8494

Figure 4: Graphical overview of the tunnel development from: (a) CAD graphic, (b) rudimentary data and (c) 3D models

<u>4.2 The ISDP Workflow - Bicycle Bridges Case Study</u>

Critical evolution of the workflow from the tunnel project and adapted to a civil structural bridge topology (Figure 5), leads to this paper's second case study. This case study entails twenty reinforced concrete footbridges for a large bicycle path network, spanning over water navigation channels and roads. The bridge topologies include various bridge superstructure solutions and varying span arrangements. Several pier and foundation solutions were also implemented as substructure designs for each bridge location.

Each unique bridge design was encapsulated into their most fundamental data, structured in dictionary key-value pairs. This fundamental data included, but was not limited to, the alignment start and end chainages, spans information, abutments types and key dimensions, piers and foundations information, bearing types, beams, spans and deck slopes. Relevant data interactions, based on real world-coordinates were also captured for each unique bridge location. Storing all the data in a universal data format allowed the authors to easily apply this methodology at scale. Each deliverable is encoded in the same way and a single source of truth is generated for each unique bridge.

Subsequently, the data was processed for each bridge, using the built-in capabilities of the chosen proprietary software. The visual-programming utility, Dynamo, facilitated this process. A unified data source was established (Figure 5a) during this process. The resulting methodology is a non-proprietary dictionary-based structure with unique key-value data entries (JSON (JavaScript Object Notation) file format). The format is both human-readable and machine consumable (non-binary text). This minimises the potential for misinterpretation by either human or machine.

(a)

(b)

(c)

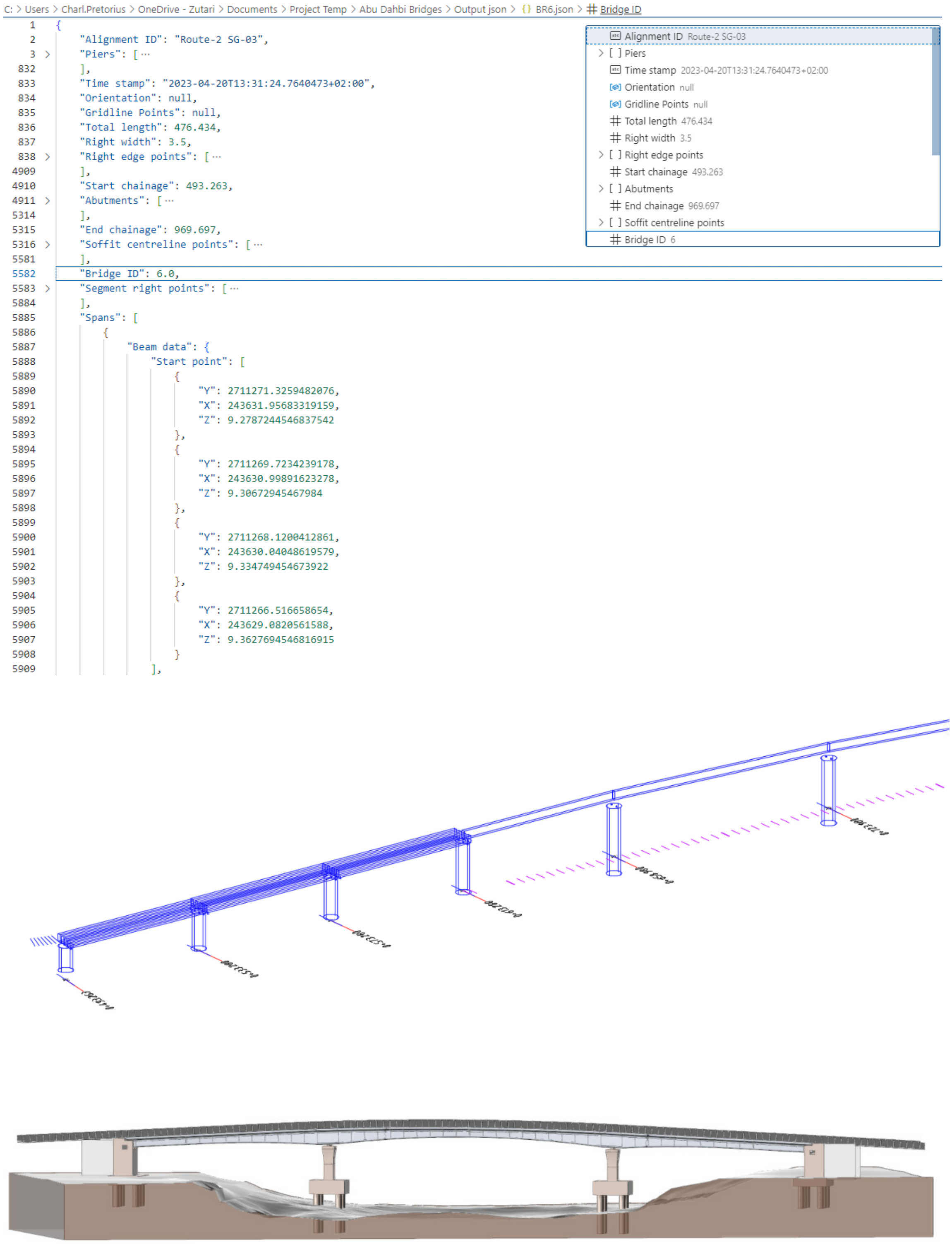


Figure 5: Graphical overview of the bridge model development, from (a) structured data, (b) simple graphic and (c) 3D model with BIM associated metadata

4.3 A Unified Data Source

When considering the modelling time and complexity, the two design project case studies demonstrated a significant improvements in productivity, turn-around time and the effectiveness that the ISDP provided. In addition, the benefits associated with a unified data source was evident (Figure 5). Despite the proprietary nature of the AEC software packages prescribed, a single unified data source was developed using non-proprietary tools (Figure 6). The systemised workflow allowed isolated data to be externalised, promoting the interoperability of the information regardless of software environments. Human error was minimised, but also readily identified where it was determined to be the primary cause of incorrect input information related to alignment geometry. Rework and markup activities were isolated exclusively to the drafting phase since the modelling workflow became fully ISDP compliant, yielding an effective and automated modelling process.

The notion of an evolving knowledge substructure came to the fore as part of the competing team dynamics; drawings were requested at the start of initial standardisation and systemisation phases (digitisation mindset), instead of closer to the end of the project where the output is produced with a high degree of automation (externalisation). These competing viewpoints demonstrate how incremental transformation forms part of a continuous process and is a pertinent driving force behind effective digital transformation.

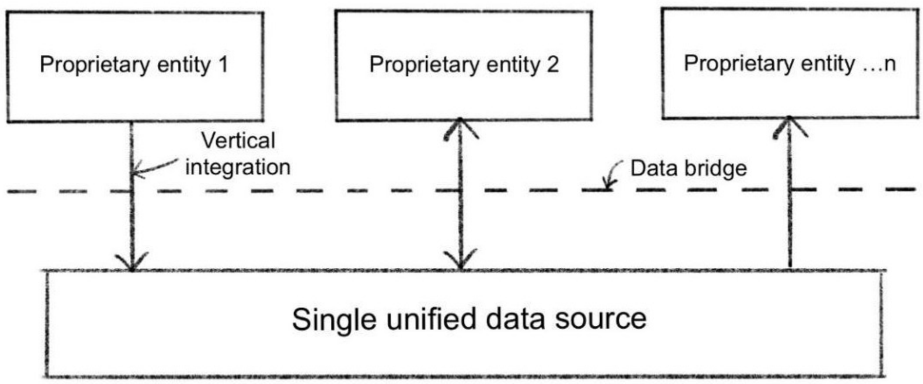


Figure 6: Schematic overview of a common data source environment bridging proprietary assets

4.4 A SMART Approach

Both the design element and the impact of digitisation on the entire ISDP of the discipline emphasised the efficacy of investing resources in research. This was purposefully initiated at the inception phase of these projects. The ISDP process facilitated the incremental digital transformation of tacit knowledge into externalised solutions for these projects. The success of the ISDP is predicated on its resulting performance that must be specific, measurable, achievable, relevant and time-bound (SMART):

1. **Specific.** Systemisation is highly specific to provide a specific function or utility with a clear standard of the information in- and outflow. Efforts are prioritised from an “information first” philosophy. Information and data give form to geometry, models or elements (outputs). Even though a component is seldom produced that can be universally utilised for another project, minor variations thereof can usually provide significant resource (time) savings.

2. **Measurable.** Given that most efforts were directed toward geometric elements, both the accuracy and reproducibility of the results served as a useful metric. Results were periodically validated against engineering calculations, such as datums of structural components.
3. **Achievable.** The systemisation process inherently reduces a task to its essential components. In a visual programming environment, this is sequential and can be broken down into more simplified processes, run independently of each other.
4. **Relevant.** Borrowing from *lean* principles, waste is reduced through adhering to the needs and requirements of a specific project, thus the emphasis of *maintaining flexibility of the process* noted earlier.
5. **Time-bound.** The information presented proved - contrary to standard practice - the necessity of dedicating a portion of time and resources to an initial research and development phase of a project. Superficial progress updates at the start of a project (such as concept drawings) are purposefully delayed or deprecated in favour of a long-term standardisation strategy.

5. CRITICAL DISCUSSION

The Digital Transformation Curve (DTC) (Figure 7) illustrates the synthesis between a modern, hyper-connected information substructure undergoing incremental digital transformation, coupled with the integrated systematised design process. The DTC takes inspiration from the Hype Cycle (Figure 1) to express digital transformation in practice over time. As with any innovation or craft activities, “hype” is generated of its supposed transformation impact, which is often mistaken for digitisation (dashed curve).

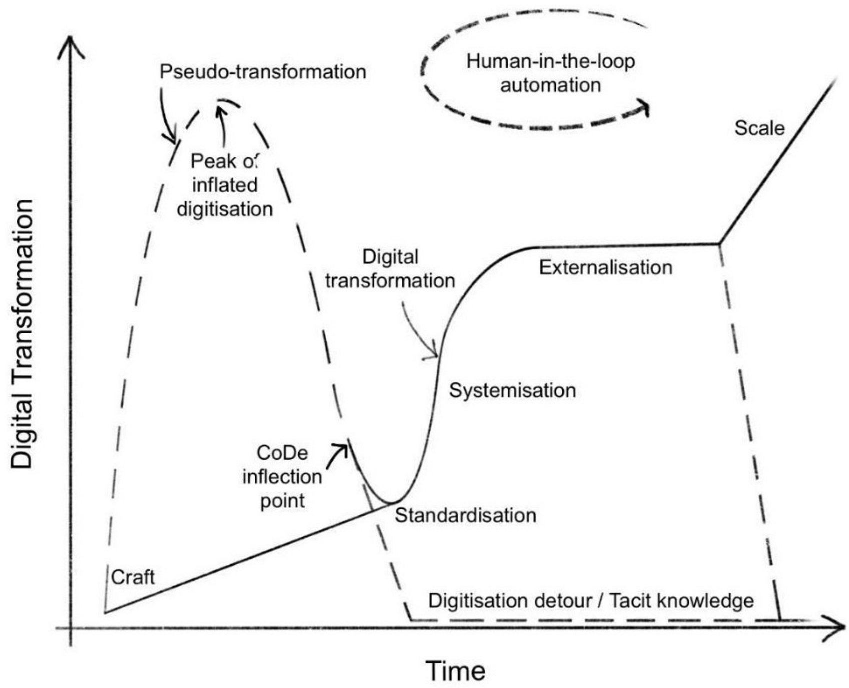


Figure 7: Graphical illustration of the Digital Transformation Curve (DTC)

The role of CoDe is to identify whether it is a worthwhile opportunity to support and develop through to an externalised state (human-in-the-loop automation), without which no transformation is realised. This in turn defaults back to a state of tacit knowledge that is not captured nor commoditised. By following the ISDP, incremental digital transformation is realised (solid curve). This in turn yields persisting automation and scaling capabilities (Figure 3).

This aligns with the findings from McKinsey (2022), who identified three factors that have emerged as critical to capturing value from digital transformation: strategic differentiation, building proprietary assets and integrating of technical talent. In other words, capturing passive tacit knowledge.

The workflows and methodologies for tunnels and bridges touched on, can be adapted for any other linearised infrastructure modelling. This paper encourages all AEC professionals to adopt similar initiatives, if only to overcome proprietary interoperability limitations. The ISDP granted the project team rapid model iteration, whilst the engineering design was ongoing in parallel, instead of sequentially. This “data first” mindset was a key ideation that effectively translated into digital transformation. The emphasis on systemising relevant engineering topologies, such as the presented examples, follows from a *purposeful* development of standards.

The case studies found that the success of an ISDP workflow is dependent on an adaptable team of T-Shaped employees, spanning specialists in engineering, modelling, and drafting disciplines with keen generalist tendencies towards an invested interest in the betterment of all and other disciplines. Such individuals also need to show a keenness towards a digital “data first” approach. Delays present within the ISDP workflow became pertinent when the project moved into the Drafting phase as a result of inadaptable superfluously needed drafting styles. The landscape of organisations and individuals within AEC is changing. Projects need to be done at an accelerated pace, often with an increasing scope, and with fewer professionals.

The question is often posed whether current professionals are failing to exploit new technologies and missing the opportunity to increase efficiency. Rather, the change of the information substructure (digital transformation) determines how we organise to avail the collective, tacit knowledge and expertise within an organisation as well as the industry. A person well versed in the language of CoDe understands the tools at their disposal and how to develop and use them to the best of their abilities - enabling others to take full advantage of externalised innovation. Human-in-the-loop automation is the deliberate effort to redirect the trajectory of digital transformation beyond the hype and fallacy that defaults to digitisation goals.

Finally, it can be theorised that the combination of digital transformation and advancements in artificial intelligence will likely see a fifth period in the information substructure genealogy. The emergence of Large Language Models (LLMs) during the last year is indicative of how we continue to organise and avail our collective knowledge and expertise in society, marking the impact of Society 5.0.

6. CONCLUSIONS

Professional industries - including engineering - are undergoing a radical transformation. The essence of digital transformation is not merely digitising old ways of working. Rather, *successful* digital transformation relies on a differentiated mindset open to new and different ways of working, reducing friction and unlocking capacity through fit-for-purpose technology.

This paper introduced two engineering design projects – one of a tunnel, the other a collection of bridges - as case studies. The ideation of an integrated systemised design process (ISDP) resulted from a strategic decision to intentionally capture the available tacit knowledge within the organisation. Computational Design (CoDe) represented the dominant mindset associated with the delivery of these projects, focusing on externalising tacit knowledge. The presented examples demonstrate the iterative evolution necessary to realise a coherent, digital engineering design and delivery process, in tandem with the lessons learned from current inefficiencies. The emergent CoDe profession speaks to an evolving information substructure – the dominant means by which individuals and organisations access specific kinds of expertise and knowledge.

The question was posed whether current professions are failing to exploit new technologies and missing the opportunity to increase efficiency. The change of the information substructure (digital transformation), with purposeful human-in-the-loop automation, determines how we organise to utilise the collective, tacit knowledge and expertise in industry and society.

Realisation of a transformed engineering industry – a Society 5.0 - is predicated on the continuous investment in resources, technology, training, retraining and T-shaped skills development by all individuals and organisations. It advances beyond the technological "hype" toward sustainable, incremental digital transformation. This is not merely for the benefit of organisations, individuals or the emerging CoDe profession, but for the AEC industry – and society – as a whole.

7. ACKNOWLEDGEMENTS

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