Technology as such is interesting but facing a big challenge in implementation when attempting to reap the benefits of digitisation

ABSTRACT

Transformer manufacturers have a tough job competing globally, as it is a traditional, highly legacy driven, price-sensitive that also demands high reliability. With shareholders targeting to improve profits, manufacturers tend to focus on production capacity, flexibility, and improving production processes. On the contrary, when production goes global, the product development process faces critical challenges in localisation of design and production, transnational design collaboration and meeting local regulations and standards. Therefore, it becomes key to international success. Digital transformation is a lever for transforming the product development process to realise the success of the global expansion. The article covers proven technologies from other industries and captures customers' requirements to order execution by managing product complexity. System driven product development can be used as a tool for system thinking by adapting modularisation, knowledge management, and design automation in engineering design processes. A combination of these technologies can be successfully used to build a paperless factory and product digital twin. This article acts as a guide to top managers in defining proven approaches to the digital transformation of the product development process and hence to achieve success.

Digital transformation in the product development of transformers is an important lever to increase profitability in transformer manufacturing. Digital transformation is a top management topic and needs a strategic approach. If appropriately addressed, it has the ability to transform the entire business. This encompasses multiple important functions, from customer requirements, product portfolio management, complexity management, design and development, manufacturing support, supply chain management. All these need to be integrated with a digital thread by analysing the existing process in four layers: product development process, sub-process, objects, and IT architecture. Following a combination of the top-down and bottom-up approach, management can successfully convert the benefits of digital transformation into balance sheet figures.

KEYWORDS

digital twin, knowledge-based engineering, product complexity management, system-driven product development, workflow automation.

Girish JOIS

Digital transformation as a backbone for holistic product development of transformers

Competitive advantage through digital tools and process

1. Introduction

Digital transformation has become a buzz word in the industry. Technology as such is interesting but facing a big challenge in implementation when attempting to reap the benefits of digitisation. There is no universal standard formula that applies to every industry. The transformer manufacturing industry is different in its own way. The degree of technology maturity and applicability varies from product to product like "of the shelf transformers", "made to stock", some "engineer to order" with high flexibility in engineering. Digital transformation poses high-level challenges in meeting each criterion. Most companies are already working on the digitalisation of their operations, and many of them are frustrated with the speed, scale and acceptance at engineers' level to deliver results according to the management's expectations. Nobody has the patience to wait for years to reap the benefit of technology. Some management with high motivation may start to push for implementation but will soon lose steam because of inherent implementation problems and lack of a deeper understanding. It depends on one's level of conviction in the digital operations opportunity. One approach could be the 'factory-of–the-future strategy'. This is more appropriate when you are in exploratory mode. It basically entails taking one physical location and designating it as your 'factory of the future.' This becomes a testing ground against which you can deploy different use cases, and test the results, see what the impact is, see the possibilities and resultant benefits.

However, if you are certain of the opportunity and you want to go faster, there is another model you can adopt. In this, you start with narrowing down the technologies, use cases, and pain-points in your operation. What are the highest-priority pain-points to be addressed? Is it the offer process? Engineering change management? Does it cost management? Or what are the use cases against these pain-points? Prioritise 8 to 10 areas that will drive 80 % of the value. Then line up projects against each of those areas with a target to achieve the results you expect.

Software solutions for the realisation of digital transformation

Digital transformation is a combination of technology, organisation process and human factors. Many of the concepts explained below can be achieved by properly customising the existing standard computer-aided design (CAD) software, product data management (PDM), and product lifecycle management applications (PLM) used commonly in engineering product development. All major companies, like PTC, Siemens, etc., offer these tools in their portfolio. Additionally, a lot of third-party configurator development tools sold in the market as

System engineering views products as complex systems and approaches the whole value chain of converting customers' specification into finished product in a holistic way

Diversified customers' requirements create market-driven complexity, while the process and production limitation create internal complexity

CPQE (configure–price–quote–engineering) solutions also help to achieve some of the objectives. However, it is important to customise the tools to meet the process objectives described below then just to implement the tool itself.

2. System engineering for collaborative product development

System engineering views products as complex systems and approaches the whole value chain of converting customers' specification into finished product in a holistic way. In product development, the mind is set to thinking in terms of individual product components, the so-called component-oriented thinking, and prevents a holistic and function-oriented analysis. System engineering handles product as an overall system. The system includes not just the product but the project, company, customer and operating environment.

System engineering [1,2] as a concept tries to address the transformer of tomorrow by following a holistic approach:

- What are the requirements, and who has requested them?
- How many variants are needed to meet those requirements?
- Which variants fulfil which requirements?
- How to address interdisciplinary product development?
- What is the relationship between the product, process and tools? How are they integrated?
- What process, methods and best practices are adapted to fulfil those needs?

The product development process and tools in today's transformer industry successfully handle standard regulatory and specific customer application requirements. However, they should be adjusted to future requirements of smart grids, which demands smart transformers. Smart transformers need to fulfil new requirements of power quality, network stability, increased reliability, advanced fault detection and prediction, energy efficiency, condition monitoring, predictive maintenance, remaining life prediction and asset management. These requirements demand system thinking in the product development process. **Thinking of the transformer not just in terms of a product but as a system with interdependent interactions in a digital world makes a good case for adapting system engineering as one of the digital transformation strategies in the transformer industry.**

3. Product complexity management to optimise product variety

Diversified customers' requirements create market-driven complexity. Limitation of the process and production creates internal complexity. Managing the complexity between customer-product and manufacturing company and arriving at a "complexity sweet spot" for a product is vital to achieving profitability.

Product complexity management [3], coming strongly from the automotive industry in managing the product variants and modular product platforms, can help transformer companies to optimise their variant offering. This can be done by adapting one or many of the following approaches:

- defining market requirements and converting them to product variants,
- developing combinatory and business rules for creating a product range on the market,
- adapting modularisation, modular product structures,

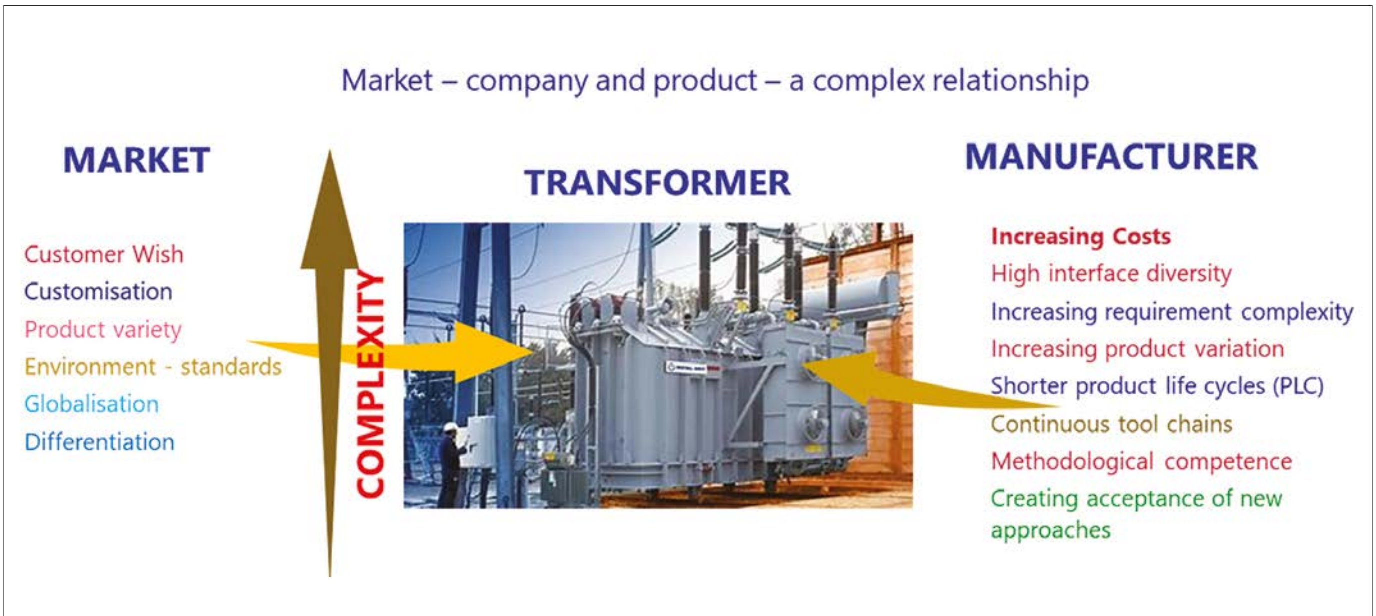

Figure 1. Different forces driving transformer complexity demand a holistic approach to complexity management

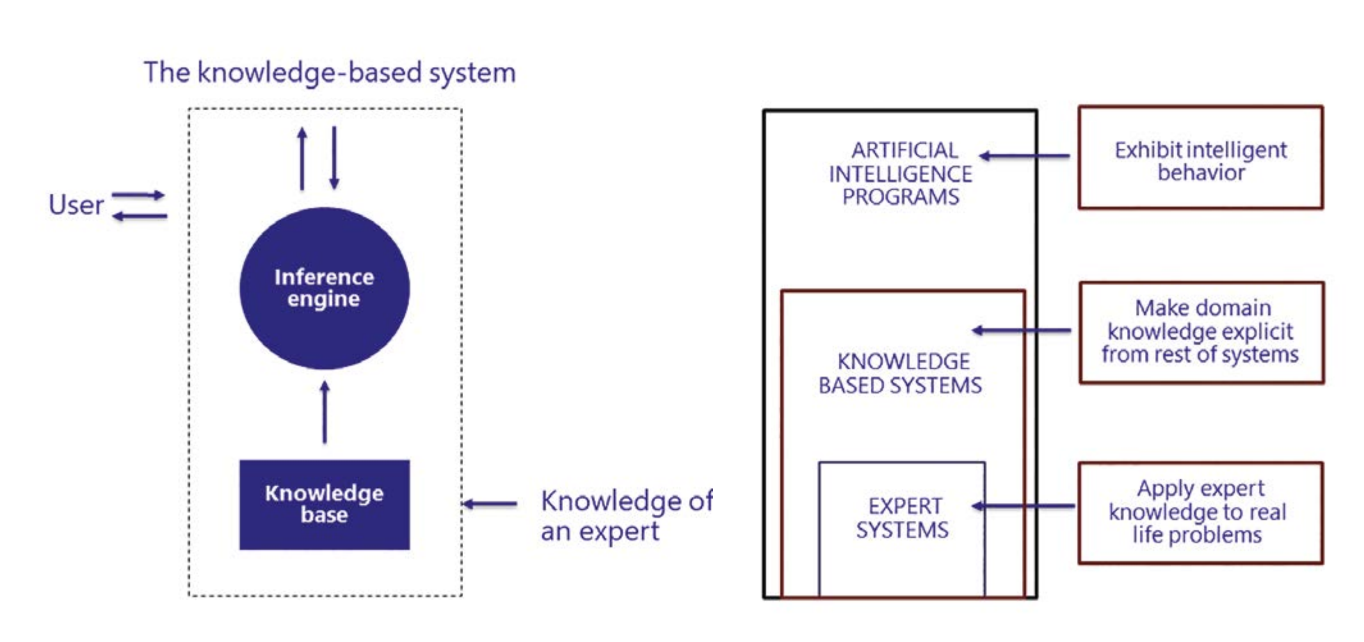

Figure 2(a). Knowledge based systems architecture

Figure 2(b). Relationship between artificial intelligence and knowledge-based systems

- applying knowledge-based engineering methods to manage complexity.

When applying this analysis to the transformer industry, the products are more standard in distribution transformers but power transformers, especially medium and low power product range, are low volume and mostly tailor-made, country-specific products. So, the product development process followed here is engineered to order. This methodology increases the cost of engineering and takes away the profit margins. There is a good scope for power transformer manufacturers to categorise their offering based on order intake history, define variant configuration considering specifications, mechanical design and manufacturing. This analysis can provide a clear understanding of the percentage of reused components, modularisation of sub-assemblies and thus help in reducing the complexity to arrive at the sweet spot balance between complexity and profitability.

4. Knowledge-based engineering (KBE) to enable design automation

KBE [4] represents the merging of object-oriented programming (OOPS), artificial intelligence (AI) techniques and computer-aided design (CAD). This method can be used as a true integrator throughout the product development process, supported by the idea of concurrent engineering. Design automation (DA) is an application that automates repetitive tasks and integrates knowledge systems into a design process.

KBE is a methodology for capturing the design knowledge into templates. These templates can be reused to design modified products without repeating complete design processes. Design automation applications capture design parameters, rules, and logics and comprise various mathematical models, company experience (knowledge base), and empirical relations. Hence, design automation incorporates a company knowledge database for the fast development of product iterations. This technique reduces cycle time and costs. New designs are more reliable as they are based on past experience and knowledge captured by software, and this also eliminates errors by incorporating standard procedures in place.

The main components of such system are GUI development (graphical user interface), design automation engine, artificial intelligence, automated geometry creation, inference engine, optimisation algorithms, machine learning algorithms, behaviour modelling, multidisciplinary design optimisation integration into existing ERP (enterprise resource planning), and PLM technologies.

The main objective of KBE is to reduce the lead-time by capturing the product and process knowledge. The core of the system is a product model where the knowledge of products and processes is stored [5,6].

Product designers in the transformer industry mostly use configurators readily available in the market and customise them for their needs. However, configurators come with their own limitations in offering flexibility in design. There have been good attempts by large transformer manufacturers to develop modular knowledge-based engineering tools internally. However, due to software complexity, long development time, effective project management skills needed, rare availability of talent in the market having both software development and transformer knowledge, the low pay-

KBE is a methodology for capturing the design knowledge into templates that can be reused to design modified products without repeating complete design processes

Knowledge management is a process used for acquiring and storing the engineering knowledge generated during many phases of engineering

off in the short term, such full-scale design automation of transformers was not developed. But with the right efforts and now existing state-of-the-art software technology, a knowledge-based engineering tool can be developed to full-scale design automation. This can especially make medium and small power transformer companies more competitive in the market.

4.1 Knowledge management for structured decision making

Knowledge management [7] is a process used for acquiring and storing the engineering knowledge generated during many phases of engineering. The knowledge which is dispersed over an organisation needs to be captured, assimilated, and made available for decision making at the right time. Knowledge acquisition becomes a critical part of building knowledge-based engineering. A software architecture for such knowledge based systems (KBS) architecture and difference between artificial intelligence (AI), knowledge based systems (KBS) and expert systems arec is shown in Fig. 2(a) and 2(b).

Design knowledge includes both the design object and the designer's knowledge, the "what" and "why" information about a design. In addition to a description of an object's physical parameters, it includes the rationale behind design decisions and results of analyses performed on the object. This knowledge gets embedded in the product architecture known as "the product model" as shown in Fig. 3(a) . A knowledge-based expert system can be built to systematically access and process this information to benefit decision-making during product development. Transformer product designers become **knowledge engineers** who help to build knowledge systems covering the entire manufacturing engineering and design.

The knowledge stored in an organisation in the form of data can be classified as structured and non-structured data. The data must be captured, processed, interpreted and stored, only to retrieve it for decision making. Variety of data points that could be captured are shown in Fig 3(b) . An "inference engine" incorporating engineers' knowledge can be used to build a knowledge-based decision system (KBS).

The **product model is a representation** of all **relevant business objects and information** in a **consistent and IT-supported structure** as the central **data backbone throughout** the product **development process** and complete **product lifecycle.**

Front-loading of a design is a concept where multiple options can be kept open during the offer stage and design definition phase, providing the flexibility to switch to alternative concepts

4.2 Front-loading of a design

Front loading of a design [8] is an upcoming concept in the digital transformation of product design, very highly followed in the aerospace industry. Natu-

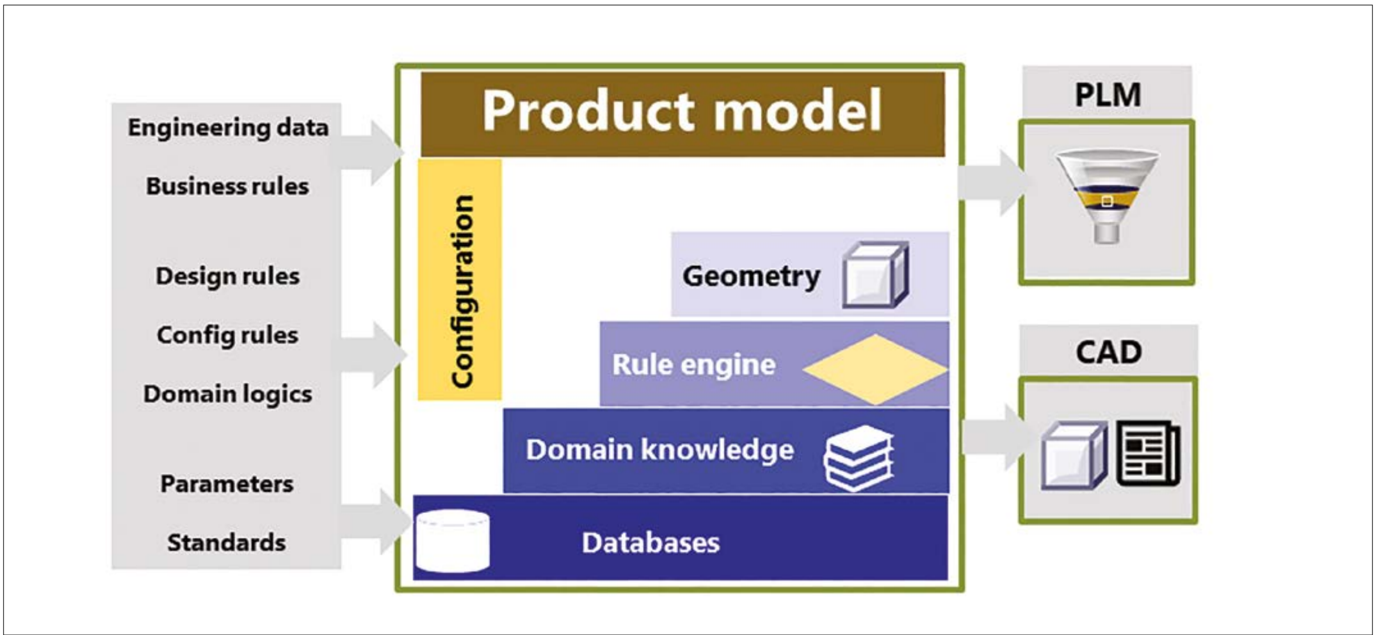

Figure 3a. Architecture and sub-modules in developing a product model – the nucleus of a knowledge-based engineering system

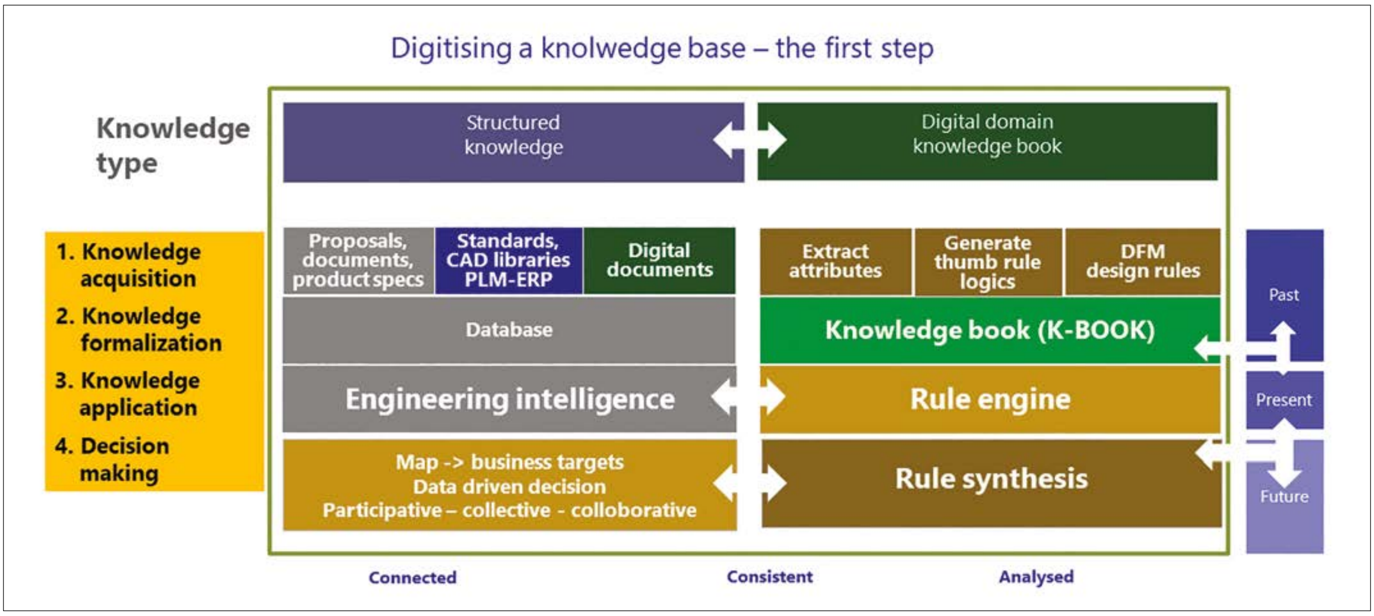

Figure 3b. Architecture for digitising a knowledge base of a company by creating a digital knowledge book – formalising knowledge acquisition and its application

rally, transformer design companies can benefit from this technological development. Aerospace and large power transformers in product development follow engineer to order, and both designs are highly customer-specific. This leads to high engineering efforts and requires a lot of interaction with the customer to achieve design maturity for production. Any change in the customer's requirement at a late stage of design will lead to a higher design and production cost. In this approach, product and engineering knowledge from earlier projects is captured, reused, and standardised to evaluate many possible design variants automatically.

Naturally, the transformer industry currently uses previous designs and adapts the design to suit new requirements. However, it is based on major specification parameters that are definable and have been captured. It does not go a level deeper into the mechanical design and does not offer an automatic recommendation of design alternatives with a considerable degree of design maturity.

The goal of this process is to achieve full maturity of each promising design variant evaluated and enabling continuous integration of changes. Multiple options can be kept open during the offer stage and design definition phase, providing the flexibility to switch to alternative concepts when the customer's design requirements change or become more mature. This ensures a large reduction in time-consuming engineering changes when a chosen design concept needs to be adjusted.

Handover process or workflow is a collection of tasks organised to accomplish a business process, where a task can be performed by software systems or manually by engineers, or a combination of both

Since design concepts are completely analysed during the front-loading part of the development process, high completeness and maturity of data are achieved very early in the design process. This ensures that development setbacks can be identified when changes in the product are still allowed and allow for a better response to changing requirements, as shown in Fig. 4.

5. Workflow automation for efficient communication

Handover process or workflow is a collection of tasks organised to accomplish a business process. A task can be performed by software systems or manually by engineers, or a combination of both.

In transformer product development, a design engineer must work in collaboration with sales, planning and manufacturing departments. **Workflow automation** [9] uses a rule-based logic to automate manual work. By leveraging a defined process and documents to be shared, workflow automation can help companies to save reaction time, diminish documentation errors, and boost productivity. As shown in Fig. 5, **this is the first step in achieving a paperless factory or what is known as a digital factory.**

5.1 Business case of workflow automation: offer process automation

In a transformer offer process, typical offer creation and costing require a huge effort from the sales. It can vary from hours to days, depending on transformer types. Many times, due to work exigencies, electrical designers get blocked by order designs, and it takes much more time for a sales engineer to get a matching design and corresponding costing. The calculation might not arrive promptly before the offer deadlines lead to frustration. **Offer process automation can provide an answer to these challenges.**

The electrical calculation is the brain behind the transformer design. It is important to create a layer of automation to optimise the designs and provide match-

> **The electrical calculation is the brain behind the transformer design, which can be automated to optimise the designs and provide matching designs to meet the business criteria**

ing designs to meet the business criteria, be it cheapest cost, optimised solution for given technical requirements, matching the logistics requirements or installation needs. This automation layer can be connected with a costing engine to provide a costing.

As explained in Fig. 6, an integrated solution has the potential to reduce the quote process from one or two days to virtually minutes. Moreover, the sales are free to create offers themselves without waiting for designers to make them independent. Offer database and CRM (Customer Resource Management) functionalities can provide a very good insight into the sales pipeline for top management.

Though there are many **sales configurators** [10] for standard needs available in the market, in many transformer segments, each offer needs to be calculated by the calculation department. Typically, transformer manufacturing companies use their own home-grown electrical calculation tools validated and proven by their design and testing department. Investing efforts to convert such old calculation tools into automated solutions to provide alternative design and cost for meeting the business criteria is worth the effort for transformer companies.

6. Good ERP and PDM system to cover the entire product development process

ERP (enterprise resource planning) systems are vital in today's manufacturing industry. Companies of all sizes have generally implemented some form of ERP system, even if it is just a combination of different software and systems used for planning and executing the manufacturing operations.

It is important for transformer manufacturers to have in place systems supporting their business from end to end. While that is a traditional **function of ERP, it also needs to provide accessibility of business information in dashboards and apps to provide better insights to the management**. They need to be connective and communicative to lower-level software applications or self-developed software tools to address a huge gambit of smaller, isolated software applications by integrating them with efficient inter-

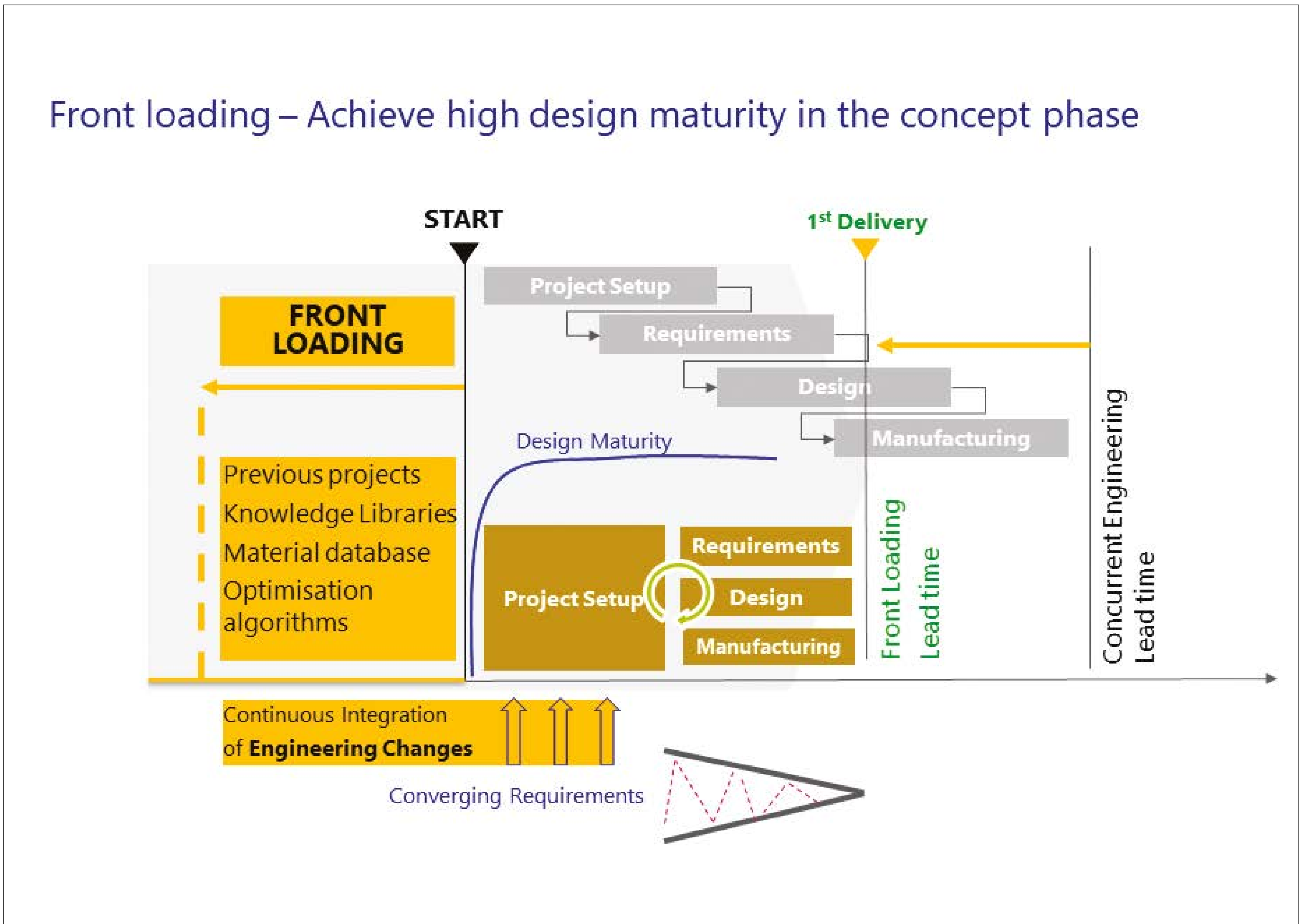

Figure 4. Innovative front-loaded design process to achieve a high level of design maturity in the initial phase itself. This can significantly reduce design lead time compared to concurrent engineering.

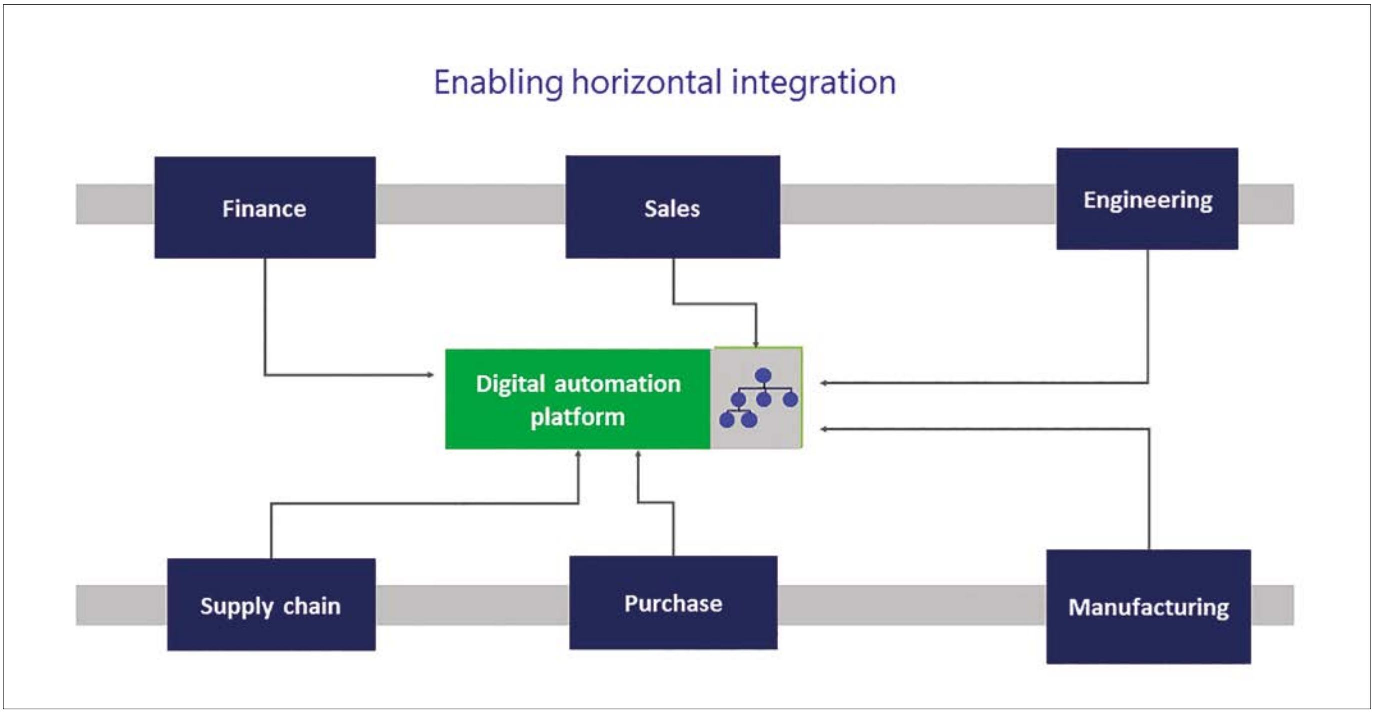

Figure 5. A concept of connecting factory functions with a digital thread by creating workflow automation enables digital integration

faces in order to drive the business value. A good example here could be a transformer electrical calculation tool that painstakingly manually combines results from a special smaller application like hot spot calculation, short circuit, impedance, force, noise calculations, costing and optimisation algorithms. This could be integrated to derive business value which otherwise would be quite difficult to achieve.

That is why implementing a modern ERP system in its standard form or with proper customisation, reflecting the manufacturing process and transactions, is a necessity for manufacturers looking to stay competitive and achieve excellence in digital transformation.

7. Cloud-based IT infrastructure as a key element of digital transformation

Traditional IT systems are not suited to digital transformations. They are not flexible enough. They are not responsive enough. They are costly to maintain, and moreover, technology vendors are moving away from supporting their on-premises applications. Cloud computing and digital transformation go hand in hand. **Among the businesses having a digital transformation plan, 85 % have benefited from a tangible competitive advantage by using cloud solutions** [11]**.** Cloud services effectively offer unlimited and dynamic IT resources, form the foundation of digital transformation, and can facilitate rapid business change. The role of IT in digital transformation is to focus on user experience rather than just on back-end IT**.**

Among the businesses having a digital transformation plan, 85 % have benefited from a tangible competitive advantage by using cloud solutions

8. Paperless factory - creating a digital thread

A paperless factory is a much larger outcome of digital transformation in product development. It is not merely digitising work instructions coming out of planning and presenting them to an operator but managing the entire digital thread from design data, passing through revision control, engineering change, work instructions and bill of materials connecting to the production department. This is a path starting from product development leading to improvements in manufacturing excellence. It has good potential in reducing the engineering effort, management overhead and delivering more reliably repeatable transformer manufacturing. A paperless system also enables the operator to become a part of the process improvement feedback loop.

Although the benefits of a paperless factory can reflect on the balance sheet in terms of reduced overheads, more importantly, they can deliver a competitive advantage as a differentiator strategy.

During the implementation, it is more important to create documents than just flat representations. They need to be interactive, enabling data to be visually queried by the operator via a simple user interface that allows for a deeper dive into the data by simply clicking or touching the item in question. Handover process automation, central database structure, CAD models and PDM structure, manufacturing bill of materials play a vital role. A near-standard, properly implemented ERP system is essential for achieving success as the master backbone for carrying out the transaction.

Although the benefits of a paperless factory can reflect on the balance sheet in terms of reduced overheads, more importantly, they can deliver a competitive advantage as a differentiator strategy

9. Digital twin

A digital twin can be defined as a continuously evolving virtual replica of a physical product, process or system. A digital twin can be either a **product twin, production twin or performance twin** [12], each relevant in its own virtual world. With the Internet of Things (IoT), every product is now getting connected. There is no difference with the transformers. A digital twin will benefit all companies in the transformer value chain, manufacturers, sub-system manufacturers, utilities and services. It will help solve physical issues faster by detecting them in advance, predicting the outcomes at a much higher degree of accuracy, assisting in designing and building better products.

Digitalisation allows for the utilisation of digital twins – a model created from design and manufacturing data that acts as a replica of a real unit, and various real-life scenarios can be simulated on a cloud platform to predict its behaviour [13].

The goal for operators of power system assets is to increase flexibility, reliability and profitability of the system, with minimum costs and maximum efficiency. This pushes operators to go for fleet digitalisation and implement a more sophisticated condition-based maintenance strategy, asset health monitoring concepts, build models to predict the residual life of the asset. This augurs well for the development of a "performance twin" [14].

In order to achieve maturity of the digital twin, digitalisation of the product development process will become increasingly important so that the operational and field data can be fed to R&D engineers to improve their designs.

The journey to create a digital twin can take a couple of years. But with prevailing technologies in sensors, IoT devices and cloud-based technologies offered by major companies as off-the-shelf products,

The digital transformation with its benefits can be a crucial lever in creating a differentiator in the transformer manufacturing market

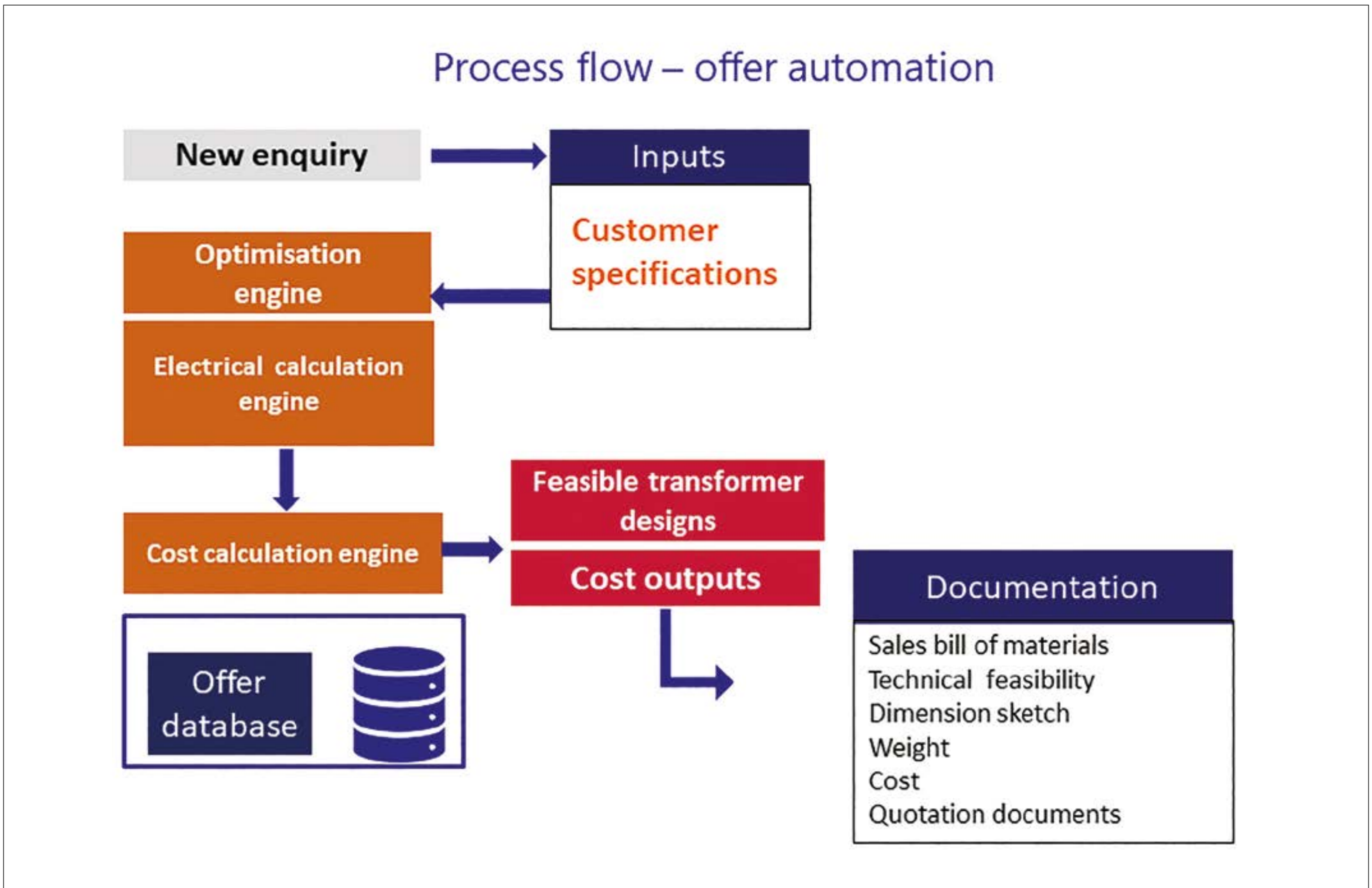

Figure 6. A concept of automation of the offer process empowering a salesperson – an example of an offer process digitisation

companies can start creating a digital twin step by step with critical data points to reduce the development time and demonstrate the business value considerably. Once proven, it can be expanded to all driving parameters, making it a complete virtual product equivalent to a real product. For utility companies, the utilisation of digital twins will enormously help to optimise their asset performance to manage their operating expenditures better.

> **A digital twin can be defined as a continuously evolving virtual replica of a physical product, process or system, which can be either a product twin, production twin or performance twin**

10. Benefits of digital transformation in the transformer industry:

Transformer manufacturing is predominantly driven by scale, capacity and cost. Transformer technology by itself is globally available and cannot act as a differentiator. In these circumstances, digital transformation becomes a key lever in creating a differentiator in the marketplace. By adopting one or more of the mentioned technologies, manufacturing companies can increase their product development productivity, reduce cycle time, be cost-effective, thus differentiating themselves on the international market and staying ahead of their competitors.

The above-explained digital technologies are being successfully implemented by big transformer manufacturers in one form or another. Siemens transformer connectivity platform Sensformer® and ABB's Internet of Things platform ABB Ability™ are major initiatives in the direction of digital transformation. Mid-size manufacturers like the SGB SMIT group also aggressively follow the digital transformation path in their product and platform portfolio to become agile, cost-effective, and internationally competitive.

Bibliography

[1] M. Maletz, J. G. Blouin, H. Schnedl, D. Brisson, K. Zamazal, *A holistic approach for integrated requirements modelling in the product development process*, Krause FL (eds), The future of product development, Springer, Berlin, Heidelberg, 2007, https://doi.org/10.1007/978-3-540-69820-3_21

[2] *Systems engineering in industrial practice* - Heinz Nixdorf Institute, University of Paderborn, Faculty of Product Engineering Fraunhofer Institute for Production Technology IPT – Project Group Mechatronic Systems Design UNITY AG, 2015, Paderbor https://www.hni.uni-paderborn.de/fileadmin/Fachgruppen/Seniorprofessur_Gausemeier/systemsengineerings/20150706_SE-Studie_enGB_Einzelseiten.pdf

[3] H. E. Waguih ElMaraghy, *Complexity in engineering design and manufacturing*, CIRP Annals, 21 July 2012, p. 799

[4] Y. Mvudi, Y., *An implementation framework for knowledge-based engineering projects*, dissertation, University of Johannesburg, 2012

[5] M. Sandberg, *Knowledge-based engineering in product development*, Luleå University of Technology, Sweden, 2003:05

[6] H. Qin, *Design knowledge capture and reuse in an integrated and collaborative working environment*, doctoral thesis, University of Portsmouth, 2016

[7] J. M. Kaiser et al., *Classification of tools and methods for knowledge management in product development*, International Design Conference - Design 2008, (p. 811), Dubrovnik, Croatia

[8] S. van der Elst et al., *D2.3: Industrial service-oriented process methodology*, 2017, ITEA3: http://www.itea3.org

[9] D. Georgakopoulos, M. Hornick, A. Sheth, *An overview of workflow management: From process modelling to workflow automation infrastructure*, Distributed and Parallel Databases 3, pp. 119–153, 1995, https://doi.org/10.1007/BF01277643

[10] M. Boucher, *Improving profitability for configured products – leveraging sales configuration and design automation*, 2015, https://tech-clarity.com/documents/Tech-Clarity-Insight-Sale-Config-summary.pdf

[11] CIF, Cloud and digital imperative, https://www.cloudindustryforum.org/content/cloud-fundamental-digital-transformation-strategies

[12] A. P. Warsaw, Industry 4.0 and digital twin, Deloitte University Press, 2017, https://www2.deloitte.com/us/en/insights/focus/industry-4-0/digital-twin-technology-smart-factory.html

[13] P. H. Singh, F. Negri, R. Fritsche, The next generation of energy transmission, Transformers Magazine, Special Edition Digitalization 2020

[14] A. Collier, *TXpert*TM *Ecosystem – Transforming performance*, Transformers Magazine, Special Edition Digitalization 2020

Author

Girish Jois has over two decades of experience in the automotive, aerospace and energy industries. He has worked at varying positions in engineering, technology, consulting, and business. Mr. Jois is currently working as a digital transformation specialist and project management officer at Starkstrom-Gerätebau GmbH, a transformer manufacturer belonging to the SGB SMIT group.