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A Dimension Reduction Approach for an Effective Manufacturing Efficiency Optimisation

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***Abstract*---- Increased competition in the manufacturing industry requires performance improvement at any enterprise level. Optimizing performance in terms of metrics such as production costs requires understanding and optimization of cost-inducing variables from product design and manufacturing. Nonetheless, the number of variables influencing production costs is very high, so it is time-intensive so computationally difficult to optimize all variables. Therefore, it is important to recognize and optimize select few variables that have high cost inducing potential. To this end, a dimension reduction approach is proposed, incorporating the mathematical modelling paradigm for dimensional analysis and the principle of graph centrality. The proposed approach incorporates current cost-inducing knowledge of variables, their interactions, and input-output relationships for various functions or device behaviour, in the form of a causal graph. To recognize conflicting effects on the variables in the graph, the propagation of optimization goals in the causal graph is verified. Following the study of the paradox, the principle of graph centrality is used to rank the different regions within the graph based on their relative importance to the problem of optimization and to classify the variables into two classes of optimization, namely less important variables and the most important variables in relation to cost optimization. The question of optimization is designed to address less relevant variables at their highest or lowest levels based on their cost interaction, and to optimize the larger variables to minimize costs. The proposed approach for dimension reduction is seen for an optimisation problem, to reduce the bladder manufacturing costs and the main mechanism for a high-field superconducting CERN magnet capable of generating 16 Tesla magnetic fields. The graph region representing the electromagnetic force and resulting stress produced during magnet energizing was found to be ranked highest for impact on the bladder and main cost of manufacture. Using a genetic algorithm solver in MATLAB, an optimization of the stress and its associated variables is performed to reduce production costs.**

***Keywords*--- Computer Integrated Manufacturing, Conceptual Modelling, Dimension Reduction, Multi Objective Optimization**

I. INTRODUCTION

Continuous development has become subsistence means for a productive manufacturing undertaking. The growth of information and communication technology and its incorporation into manufacturing in recent times has further allowed companies to meet consumer needs in an economical and sustainable manner. In order to stay competitive on the market, manufacturers need to ensure optimized capital, energy and consumables usage as well as extended product life. Therefore, for a company, optimizing a process or product design to boost performance is essential. Manufacturers measure performance using key performance indicators like cost, quality, and productivity. These metrics are often functions of variables of design and construction that need to be modelled and optimized [1]. Therefore, adequate information about the design and manufacturing process of the product is required to model its impact on performance indicators. Difficulty occurs when attempting to model these performance metrics, which are inherently complex and spread across several realms including product actions, physics of manufacturing processes, and planning output. In addition, the optimization of a performance metric requires that manufacturers find optimal values for all contributing variables. Choosing optimal values for all variables regardless of their level of effect on results is cost-intensive in computational terms. Reduction of dimensions in the product optimisation or machine learning area is not a new phenomenon. Nevertheless, in manufacturing performance optimization models there is a lack of systematic techniques which embed domain knowledge. Therefore, a multi-domain approach is needed to optimize performance indicators with the aid of computational modelling and simulation. These approaches will help producers:

1) Define the interrelationships between variables in a performance modelling system;
2) Incorporate knowledge of various domains for modelling performance metrics, and

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3) Reduce the number of variables required for performance optimisation.

This research focuses on developing a new approach for the reduction of dimensions that incorporates graph-based modelling of performance measures across various domains using the conceptual modelling paradigm for dimensional analysis (DACM) and variable clustering using the principle of centrality in graph theory and analysis of networks [2], [3]. The approach is tested using a case study to fabricate the main and bladder structure at CERN for a modern superconducting magnet. The remainder of the paper is structured as follows; Section 2 includes a background discussion on conceptual modelling, optimization dimension reduction, and the definition of graph theory and network applications as a centrality.

II. BACKGROUND

Conceptual modelling and simulation:

Conceptual modelling is the abstraction of a model from a proposed or actual system. DACM paradigm as a mathematical modelling method originally developed as a specification and testing technique for complex systems but extended to several different cases such as additive manufacturing, machine learning, and multidisciplinary design optimisation. DACM's main goal is to derive and encode information of various types (expert literature, empirical / experimental, and equations) in the form of a causal diagram. The DACM method begins with functional system modelling and assignment of fundamental variables to the various model functions. In the causal graph the functions, associated variables, and symbolic equations are described in the form of the cause-effect relationship between the functional model's fundamental variables. The mathematical machinery for testing the propagation of an objective in a causal network is based on the theory of Pi (π)- theorem of the Vashy-Buckingham and the theory of dimension analysis (DA) [4], [5]. You may obtain an adjacency matrix or multiple domain matrix (MDM) from the causal network that describes multiple domains. A MDM is a systematic extension of the matrix design structure (DSM), which is popularly used in system decomposition, integration, and complex system design. This matrix encodes a rich data structure capable of representing information derived from the variables of the multi domain system. In this research the representation of the matrix is qualitatively tested to test for conflicting effects in the objective imposed by the variables of the method. A dimension reduction approach follows the qualitative analysis to rank order the device variables and form the objective principle of optimization.

Dimension reduction:

High dimensionality is a fundamental problem in the field of science and engineering, during computational analysis. Computationally expensive and resource-intensive methods of optimization are required in manufacturing to simulate high-dimensional problems such as planning output, scheduling, and optimizing performance. Shan and Wang provided a survey of common strategies such as decomposition to break up the problem of optimization into simpler and smaller measures, and screening variables to classify more important and less important variables as possible means to resolve the high dimensionality of engineering issues [6], [7].

A screening using the theory of graph centrality and node ranking is conducted in this research to identify variables as either low impact or high impact, based on their effect on the output objectives. After the classification the problem of optimization is broken down into two stages. Next, in the output targets, the low impact variables are set at their highest or lowest values depending on their relationship with the goal variables. Second, optimization is done for only the high impact variables based on the success parameters that have the low impact variable values set. The screening using graph centrality and ranking of nodes is seen in the next subsection 2.3

Graph centrality and node ranking:

The consumer is also interested in understanding what are the most important nodes in a graph-based representation of a network consisting of a large number of nodes. It makes the user shift their focus to that part of the graph (or network) that has the most impact on the defined structure. Parameters of graph centrality are used to rate nodes and consider the most prominent nodes in a complex network. Its most popular applications include wireless network applications, reduced network traffic, and analysis of social networking networks. There are many tests for graph centring, Freeman offers one of the earliest empirically based centrality measures in complex networks. The author defines three measures which can be used to obtain a score for centrality in a graph, namely degree, between, and closeness. Borgatti and Everett have established a standardized system for centrality assessment scores in diverse social networks. They describe centrality as the contribution of the node to the network's cohesiveness. These also have mathematical expressions for centrality score calculation in complex networks. A

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centrality calculation algorithm similar to the PageRank algorithm, proposed by Google's Brin and Page, could automate the process of ranking the various nodes.

PageRank is a method of network ranking built in Google's search engine results for measuring ranks of web pages. An enhanced version of this algorithm is used in applications that go beyond the search engine rankings, which include graph-based system requirements impact analysis and graph-based selection functionality. A dimension reduction strategy is built in this article, based on the system's causal graph representation [8]–[10]. Node ranking algorithm along with measurements of graph centrality are used to classify most important variables within the method. The variables are categorized into two categories in the causal graph; high ranking / high impact variables, and small ranking / low impact variables. Therefore, only a smaller subset of the complete variable list that has a high impact is used to refine the performance goals, minimizing computational costs. A case study of the manufacture of the key and bladder system for superconducting magnets in Section 3 describes the technique for dimension reduction using node rating.

III. COMBINED CONCEPTUAL MODELLING AND DIMENSION REDUCTION METHODOLOGY

The European Centre for Nuclear Research (CERN) has developed conceptual designs of superconducting magnets with a field strength of 16 Tesla (twice as much field strength as the latest Large Hadron Collider working prototypes). Three prototypes for prototype manufacturing are being considered in the conceptual design phase; the cosine theta design, the block design and the traditional coil design. The magnet and its support structure differ in scale, performance, fabrication, and assembly processes in these three designs. Electromagnetic forces attempt to stretch the coil when the superconducting magnet is energized. Those forces cannot be sustained in stress by the coil itself. Researchers are therefore proposing a bladder and key (made of stainless steel, SS) system to combat this force during service, and to have good control during assembly to produce cost-effective magnets. The design and manufacture of the various components which make up the magnet becomes challenging provided that it is a question of multi-criteria design optimization [11], [12]. The greater the number of design variables, design constraints, material selection criteria, production parameters and finished product functional specifications, the greater the question of optimisation is computational. The cosine-theta architecture structure for the magnet is used for case study in this research. The methodology developed is shown in Figure 1 as a three-step approach which includes modelling the system using DACM, dimension reduction approach to finding most influential variables, and solving the problem of optimisation. The DACM system is used during energizing to model the magnet's behaviour (expansion of magnet coil due to electromagnetic force or Lorentz force).

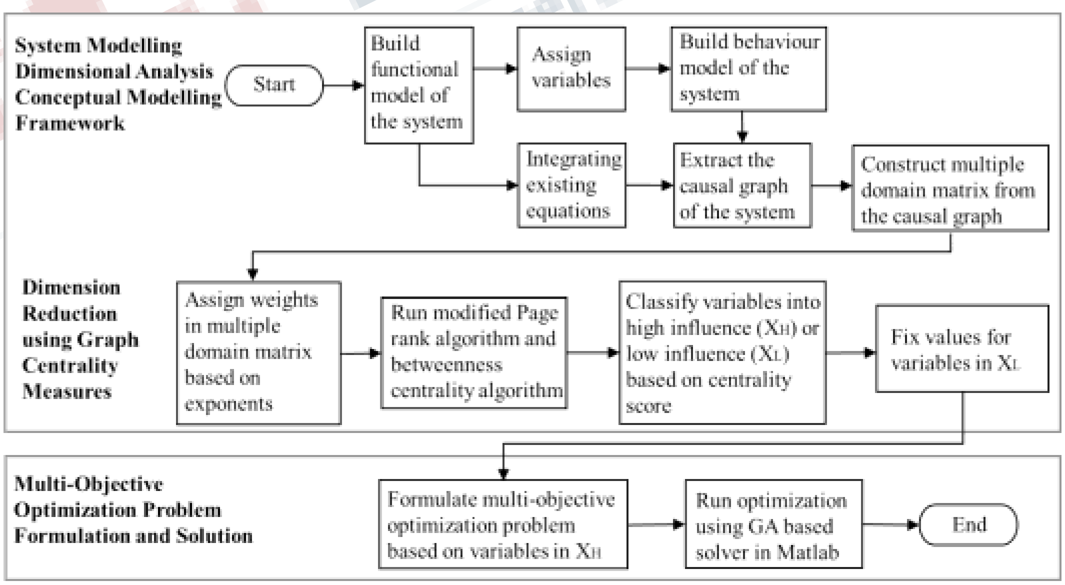

Fig.1: Combined Conceptual Modelling and Dimension Reduction Methodology

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In earlier research, the step-by-step conceptual modelling approach using DACM is clarified. The magnet's numerous support mechanisms counterbalance the electromagnetic force to avoid magnet displacement. In this case study, for simplification the electromagnetic force is supposed to be counterbalanced by the pre-stress given by the bladder and main mechanism. The system's functional model is developed from an abstract definition to a fidelity model based on elementary phenomena from the classical electrodynamics domain and failure theory, as shown in Figure 2a. Figure 2b shows the resulting causal graph of the variables built on the basis of existing equations describing the different functions of the system. Figure 2c displays a simplified version of the cosine theta magnet concept used in this case study. The causal graph maps the variables from the functional domain to the technical domain (used by designers to describe design parameters such as product and material geometry), and from the technical domain to the process domain (used by manufacturers to assign process parameters and measure production costs). The nodes are green (independent variables), blue (intermediate variables), black / gray (exogenous variables), and red (target variables), respectively. The arcs that link the nodes represent the interconnection between various variables as well as the exponent from existing equations of that relation. If the increase in the nth node increases the (n+1)th node and a "–" relationship, if the increase in the nth node decreases the (n+1)th node, a "+" is assigned to the node link which denotes the relation. First, it constructs a multiple domain matrix from the causal network. The MDM is a sparse, square matrix representation of the structure of the system that condenses knowledge of all variables with their weights obtained from the causal graph (network) via the functional, design and manufacturing process domains. The MDM can be viewed as a set of design structure matrices (DSM) in each domain, mapping the domain variables to themselves, as well as variables from other domains representing the entire system structure. The MDM's first column is composed of all machine variables. The MDM is a scalable matrix that can handle very large structures, where each DSM can contain any number of finite variables.

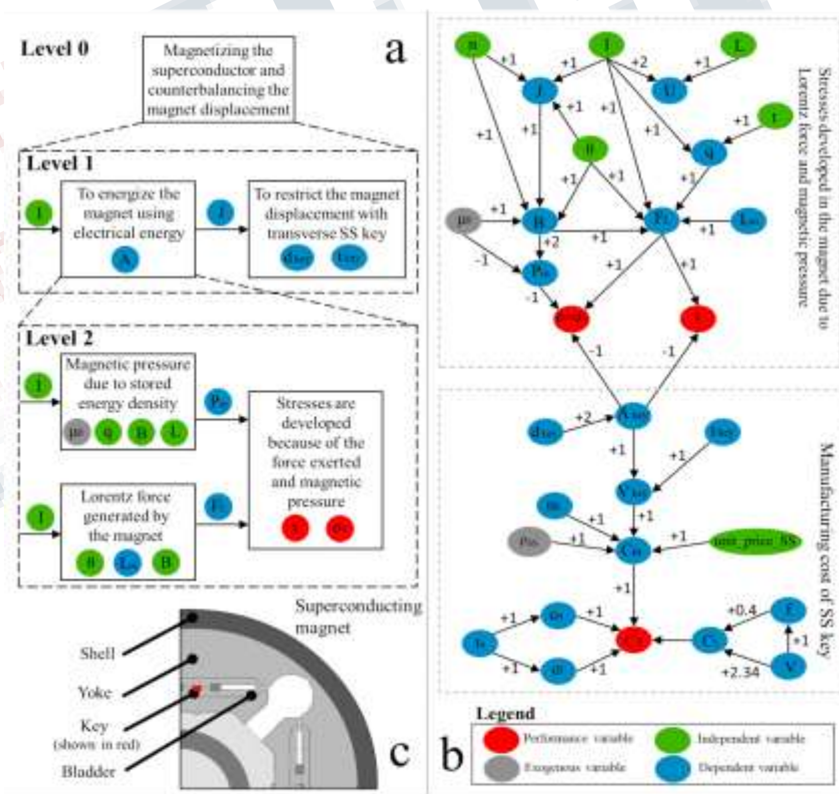

Figure 2: (A) Functional Model Describing Expansion of Magnet Coil Due To Electromagnetic Force; (B) Causal Graph Depicting Magnet Behaviour, and (C) Simplified Cosine Theta Magnet Design

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To rank nodes in the causal network based on MDM, a weighted PageRank algorithm and between centrality scores are employed. The PageRank algorithm calculates a probabilistic rank matrix, which provides an approximation of the value of all nodes in the network based on the nodes 'in-coming and out-going relations in the causal graph. The PageRank algorithm is versatile, and the weights within the causal network can be changed. A rank order for the nodes is obtained based on the calculated centrality score from the PageRank algorithm. The centrality score for between is also determined for the MDM to verify the results obtained from the PageRank algorithm.

Unlike PageRank, which is an Eigen vector centrality metric, the centrality of the between is a metric of the control a node in a network has over the distribution of information across the network. The score tests to what degree a node lies in the shortest path between the hub and the goal node. The higher the between score means that the nucleus and objective nodes are more important to the network. Therefore, between score declares node categorization as being of great importance and nodes of low importance. Using the PageRank algorithm and between score tests, the variables are categorized into XH (high influence variables) and XL (low influence variables) matrices.

The weighted PageRank results and the variables between scores. When it has high score in both PageRank and between centrality measures, a variable is considered to be of great importance. The ranks are clustered based on the highest ranking node, and a threshold of 0.3 is chosen based on the rank distribution to categorize the variables. In XH matrix, the high scoring variables are stored and the low scoring variables are stored in the XL matrix.

IV. CONCLUSIONS AND FUTURE WORK

Reduction of measurements allows for quicker and cheaper optimisation of product design and output assessment of manufacturing. A dimension reduction approach is suggested in this research using the DACM system and the principle of graph centrality to estimate and reduce the manufacturing costs of new products during the conceptual design stage. The suggested approach breaks down the optimization problem into two stages by categorizing variables into low-level variables whose values are prefixed during step 1 of optimization, and high-level variables that are optimized using a solver (step 2). The technique for optimizing the bladder's manufacturing cost and main mechanism of a modern high-field superconductive magnet used by CERN is being demonstrated. The two-step optimization approach eliminates the effective number of variables that need to be optimized in order to achieve the lowest production costs. The reduced variable list reduces the time of measurement during optimization and thus allows for cheaper and quicker optimisation. Future work focuses on extending the case study to include other 16 Tesla magnet components and validation using actual data from the manufacture of CERN prototype magnets.

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