Comparison of Emerging Manufacturing Concepts

A. Tharumarajah A. J. Wells L. Nemes

CSIRO Manufacturing Science & Technology, Preston, Victoria, Australia

ABSTRACT

The current and continuing focus on agile manufacturing will pave the way towards organisational structures with very high operational flexibility and the ability of systems to transform their internal structure and technology as needed. A promising structure, in this respect, is a conglomerate of distributed and autonomous units which operate as a set of cooperating entities. In this paper we examine the emerging Bionic, Fractal and Holonic concepts of manufacturing. After briefly describing their features a critical comparison is made between the concepts on their design and operational features. This comparison discusses some of the essential features including the autonomy of units and the types of regulatory mechanisms and adaptation requirements that need to be considered to properly manage the complex interactions that may ensue due to the distributed nature of these systems.

1. INTRODUCTION

Over the next decade there will be developments which may change the manufacturing scene to base production on smaller units with greater flexibility. This shift, as already evidenced by the focus on agile manufacturing, will have a deep impact on the design and operation of future manufacturing systems. Current organisations will be replaced by more innovative organic structures that may offer a very high operational and structural flexibility. In this paper we examine the emerging concepts of Bionic, Fractal and Holonic manufacturing which advocate such systems, and compare their approaches to the design and operation of manufacturing systems.

The next three sections review the emerging concepts. Following this, the design and operational principles of the concepts are delineated and compared.

2. Bionic Manufacturing

The Bionic Manufacturing System (BMS) [4-7, 16-17] draws parallels with biological systems and proposes concepts for realising essential properties of future manufacturing systems.

A biological system exhibits many features including autonomous and spontaneous behaviour, and social harmony within hierarchically ordered relationships. Structurally, the cell is the basic unit which comprises all other parts of a biological system. Cells are basically similar, but differentiated by function, and are capable of multiple operations.

Cells act as building blocks to make up the hierarchical layers in organisms. Thus, tissues (e.g., muscle tissue) are formed by cells with similar functions and shape. Different tissues combine to form organs with a particular function (e.g., heart). Organs, in turn, group together to form body systems (e.g., digestive system made up of the stomach and small intestine), and the systems make up the complex organisms.

The stability of the internal chemical environment of a living organism is maintained by means of regulating the rate of its metabolic reactions. Within a cell this is done by the enzymes that are produced by the cells. These enzymes act as catalysts to speed up or inhibit reactions. A second level regulation is done through hormones that are secreted by cells and transported in body fluids to other parts where they exert a specific physiological action. An example of this action is colour change in some animals in response to danger. Since hormonal regulation can be slow, a central nervous system exists to deal with situations requiring rapid reactions to changes in the external environment.

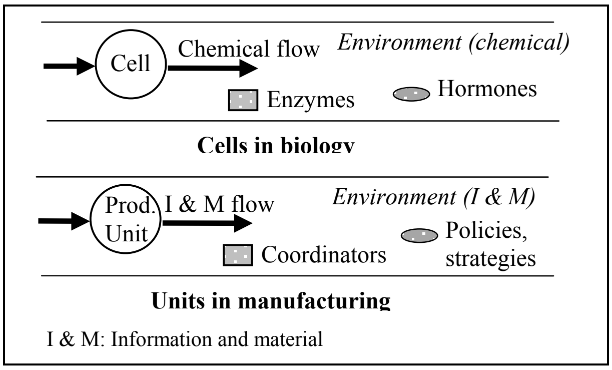

Figure 1: Similarity of Biological and Manufacturing Structures

The above properties of biological systems have many similarities to the operation of manufacturing units as shown in Figure 1. The units obtain the needed inputs from the factory floor environment and perform operations. Outputs of these operations flow back to the environment. Like enzymes, coordinators may act to preserve the harmony. Also, regulatory schemes similar to hormones may include policies or strategies that have a longer term effect on the environment, for example changes to shop-floor practices. Even centralised control may be applicable to urgently react to certain contingencies.

In addition, the manufacturing units can act similar to cells as building blocks to derive hierarchical control structures, such as shops, factories and business units. In such structures, each layer in the hierarchy supports and is supported by the adjacent layers. When specification is given at the top-layer, it passes down layer-by-layer to the bottom and finally as tasks.

In a bottom-up process, the units' actions cumulate and manifest in an operation of the whole system.

BMS uses these parallels in manufacturing to put forward modelling concepts and applications. For instance, Okino [7] foresees a bionic factory that will operate with distributed components (machines, AGVs etc.) having quasi-life. The components, including the part, communicate and inform each other of the decisions made by themselves. In fact, he compares the knowledge of the processes possessed by the components as genetic information. Thus, typical information of how a part should be made or assembled resides in the product, and it communicates with the machines and decides on the schedule. With this information a part, represented by a general modelling element called a modelon, can communicate with the modelons representing the required resources (i.e tools etc.) and cooperate to produce the physical workpiece.

Further, Okino [6, 7] exploits the properties of biological growth process (morphology) to suggest a bionic type of design room. For instance, a typical design activity can be carried out by developing a specification in the top modelon (a parent modelon). This is followed by gathering the required sub-modelons from a modelon base that execute related lower level functions to realise the specification. The manner in which this propagation is implemented is through a self-organising process, where each higher level modelon passes DNA[1] type information to lower levels, and gathers the required sub-modelons.

Actual applications of bionic manufacturing have been planned under the IMS/NGMS (Intelligent Manufacturing Systems/Next Generation Manufacturing Systems) project and by the CAM-I consortium.

3. FRACTAL FACTORY

The main characteristic of fractals is self-similarity, implying recursion, pattern-inside-of-pattern. Mandelbrot's sets [1] display self-similarity, because they not only produce detail at finer scales, but also produce details with certain constant proportions or ratios, though they are not identical.

The concept of fractal factories [18] draws on such features of fractals, and proposes a manufacturing company to be composed of small components, or *fractal entities*. These entities can be described by specific internal features of the fractals [12]. The first feature is self-organisation that implies freedom for the fractals in organising and executing tasks. They may choose their own methods of problem solving including self-optimisation that takes care of process improvements. The second feature is dynamics where the fractals can adapt to influences from the environment without any formal hindrance of organisation structure. The third feature is self-similarity interpreted [11] as similarity of goals among the fractals to conform to the objectives in each unit.

In addition to the above characteristics, there is a need for the factory fractals to function as a coherent whole. This is achieved through a process of participation and coordination among the fractals, supported by an inheritance mechanism to ensure consistency of the goals. In fact, according to Strauss and Hummel [12], fractals are always structured bottom-up, building fractals of a higher order. Units at a higher level always assume only those responsibilities in the process which cannot be fulfilled in the lower order fractals. This principle guarantees teamwork among the fractals and also forces distribution of power and ability.

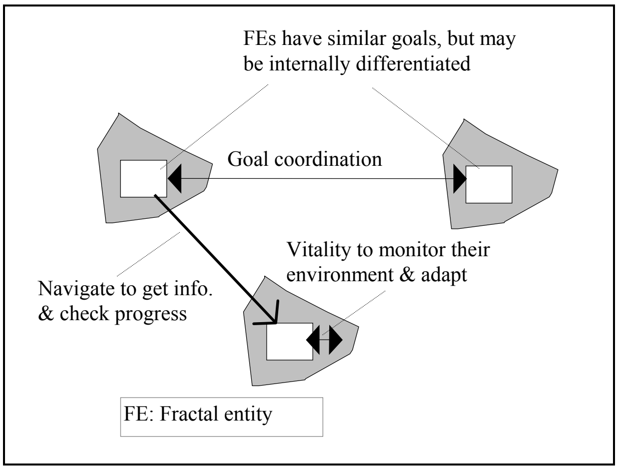

Figure 2. Operation of Fractal Entities

During operation, as shown in Figure 2, cooperation between factory fractals is characterised by high individual dynamics and maximum ability to adapt and react to the influences of their respective environments. This ability is called vitality, and as Sihn [10] states, it is used to record and evaluate those variables internal to the fractals that are affected by the environment. This information is used to measure for change against the characteristics of six specific levels of the work environment: cultural, strategic, socio-informal, financial, informational and technological.

The Fractal Factory has a flexible and efficient information and navigation system. Fractals navigate in the sense of constantly checking target areas, reassessing their position and progress, and correcting if necessary. Thus, relevant organisational structures will be continuously optimised and adapted by each individual fractal in the light of any changes.

Applications of the concepts of Fractal Factory have been reported. For instance, a case study at Mettler-Toledo (ibid.) proposed self-managing fractals for developing new products and technologies, and for managing production. It reports implementation of variable layout, together with flexible use of personnel to enhance adaptability to changing market conditions. Future applications of this concept are also proposed under the IMS/NGMS project.

In fact, many isolated elements of the Fractal Factory can be found in daily practice, including [p. 215, 18]: business units, an orientation towards business processes, the introduction of manufacturing segmentation and cellular production structures. Nevertheless, these do not contain the full solution

[1] deoxyribonucleic acid

as more work is required to coordinate the actions of the individual fractals and put in place mechanisms that permit self-organisation and dynamic restructuring.

4. HOLONIC MANUFACTURING

The word holon [2] is a combination of *holos* (a greek word for whole) with the suffix *on* which, as in proton or neutron, suggests a particle or part. It describes the hybrid nature of sub-wholes/parts in real-life systems, that is holons simultaneously are self-contained wholes to their subordinated parts, and dependent parts to a larger whole that contains it. This observation comes from analysing hierarchies and stable intermediate forms in living organisms and social organisations, and simply reinforces that although it is easy to identify sub-wholes or parts, wholes and parts in an absolute sense do not exist anywhere.

The two essential attributes of holons are being autonomous and cooperative. Being autonomous it exhibits its wholeness to be self-regulating, while cooperation exhibits its partness to be integrative. Holons can be defined by their functions or tasks, and their operation can be defined by a set of fixed rules and flexible strategies. The rules, termed the system's canon[2], determine its invariant structural configuration (i.e., whole-part relations) and/or functional pattern, while strategies define the permissible steps in the holon's activity. Using flexible strategies, a holon self-regulates and reacts to changes in the environment, and the changes are fed back to the centre controlling it. In response the centre continually adjusts its course of action.

Koestler's work provides useful background and is a source of inspiration. His underlying concepts of holons are adopted by the Holonic Manufacturing Systems (HMS) Consortium under the IMS) Program. However, to be applicable, more specific and accurate working definitions for terminologies such as holon, holarchy, holonic systems, are developed by the Consortium. A selection of the consortium glossary entries on the most important terms are presented below [9]:

[Holon:] An autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects. The holon consists of an information processing part and often a physical processing part. A holon can be part of another holon.

[Autonomy:] The capability of an entity to create and control the execution of its own plans and/or strategies.

[Co-operation:] A process whereby a set of entities develops mutually acceptable plans and executes these plans.

[Holarchy:] A system of holons that can co-operate to achieve a goal or objective. The holarchy defines the basic rules for co-operation of the holons and thereby limits their autonomy.

[Holonic manufacturing system:] A holarchy that integrates the entire range of manufacturing activities from order booking through design, production, and marketing to realise the agile manufacturing enterprise.

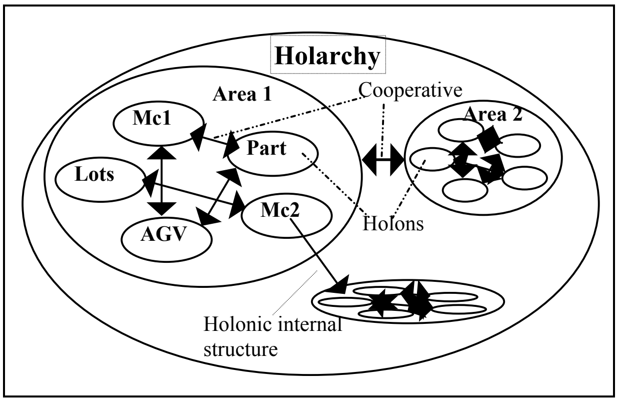

FIGURE 3. A Holonic System

Feasible applications of Holonic Manufacturing concepts have been tested for machining, assembling, transport and continuous manufacturing. Detailed examinations of concepts have been undertaken[3]. For example, operational aspects of the concept are explored to schedule a set of holons in an environment of production cells and robots having distributed control. Application to realise a flexible and reconfigurable robotic system is proposed. A fixturing holon is proposed as an intelligent object to clamp parts for machining. Studies outside the HMS Consortium include that of Suda [13, 14] and Mathews [3], though these are mostly of conceptual interest.

The range of promising applications of Holonic Manufacturing transcends the traditional views of restricting autonomous operations to machines, cells or other geographically located units and humans. In fact, a holon (according to the definition) can be purely informational (e.g. a process plan) or they can be physical objects that are endowed with additional information processing capabilities (e.g. machines). In some sense, holons of HMS are similar to the modelons of BMS. But, holons and their organisation into holarchies exhibit whole-part relations in contrast to the layered representation of BMS.

5. COMPARISON OF CONCEPTS

The above concepts describe, in quite general terms, the underlying principles and features of designing manufacturing systems which are highly flexible in their structure and operation. However, the concepts differ in their approach and the following sub-sections highlight these on some critical

2. Can be explained as follows [8]: from the point of view of the entity, the behavioural impulses would be creative, while the necessary configurations of the outer world winnow these through exigencies of the actual situation, thereby diminishing their numbers to a realistic few.

3. Due to the restricted circulation of these studies references to studies undertaken have been ommitted.

system parameters pertaining to the general, design and operational features of manufacturing.

5.1. General features

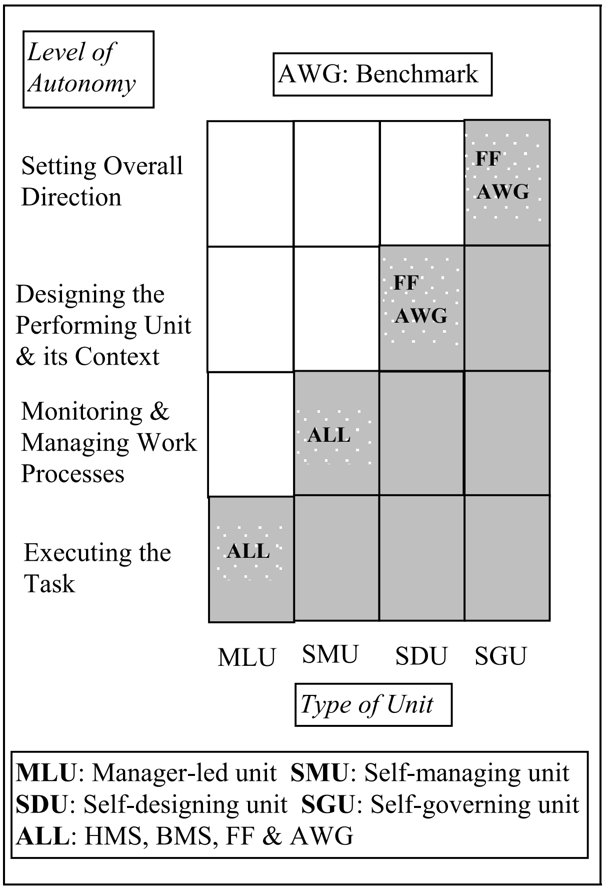

Figure 4: Level of autonomy of the units

The emerging concepts of manufacturing systems have been derived from some underlying similarity with naturally occurring systems, be they biological or social. But, how strong is the analogy? Does it require extensive conceptual developments? Clearly, BMS has more direct relevance in that direct application of concepts and features of biological systems is possible. HMS and FF, on the other hand, use the analogy to define the very basic concepts of the manufacturing systems they foresee. Thus, extensive development may be required to further define the design and operational features.

The concepts describe self-organisation as a core characteristic, but to what extent can they support self-organisation in manufacturing. To answer this, consider the framework given in Figure 4. It is based on the one proposed by Hackman for Autonomous Work Groups - AWGs [12]. As shown in the vertical axis, the extent of self-organisation is given by the progressively increasing levels of autonomy or responsibility that can be endowed to a unit. The horizontal axis indicates the type of unit corresponding to the level of autonomy endowed. Using this framework, when the level of autonomy is restricted to the execution of a task, it may result in a Manager-led unit similar to Tayloristic type of management. At the other extreme, a Self-governing unit assumes total responsibility including setting the overall direction. As the unit moves towards this end, its sphere of influence extends beyond the immediate control of the processes to other aspects of the organisation. These include both human and business sides.

Considered within this framework, the focus of the concepts vary somewhat on the types of units envisaged. Holons (and holarchies) are basically formed on a functional decomposition of a system, i.e. the tasks to be done. This way it may focus on Self-managing units with limited capabilities for self-design or self-governing. Similarly, BMS considers the functions of modelons (cells) with multiple operations where the focus is on self-management. On the other hand, the features of a fractal entity promote continuous adaptation to changes in the business and operational environment (i.e., the six levels of the work environment). Consequently, fractals may be seen as dynamic with the ability to reconfigure themselves in response to the environment. Thus, it may be designed to be a self-governing entity, more like a business unit.

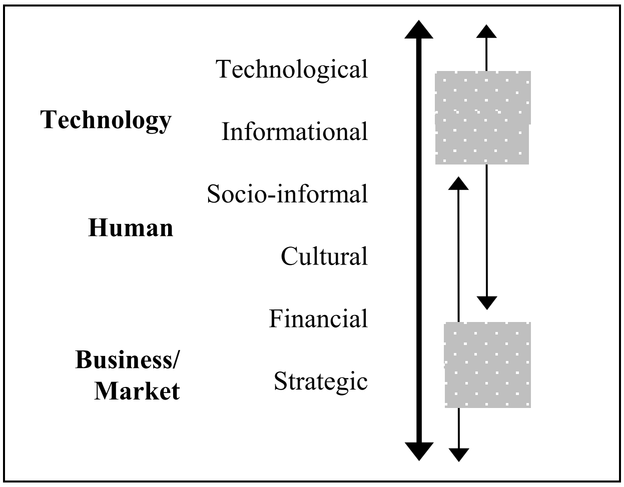

Figure 5: Focus of development of the concepts

However, this seemingly broader perspective of autonomy of the fractals may not necessarily translate to the development of such units at the technology end. Consider the six levels of the environment proposed by Sihn [10] transposed as a continuum in Figure 5. The technology end of the spectrum addressed by the Fractal Factory is more towards applying principles of flexibility in layout and application of technology such as Kanban and JIT. Whereas, both HMS and BMS in addition to such applications tend to develop technology that make the equipment and devices themselves display autonomous behaviour in operation. This provides these physical units with intelligence and the ability to function as quasi-living things. This focus, however, may increase the concentration on automation to the neglect of human and business elements during design.

5.2 Design Features

The design of these systems, in particular the architectural aspects, stresses recursive part-whole relations. However, the approaches differ in the manner in which these aspects are used to describe and design the basic units of manufacturing and their autonomous properties (for a detailed discussion see [15]).

The definition of a unit in BMS is a modelon that may be capable of multiple operations. These may be defined through repeated cell division (recursion) using DNA type growth process. Definition of holons are similar. Their definition, however, may be carried out top-down by defining the holarchy first and the constituent holons subsequently. Designing fractals requires consideration of the six levels of environment as discussed before. Their design is bottom-up similar to BMS, where the operations are assigned to lower level fractals according to their ability before higher order fractals are formed to subsume the already assigned functions.

The design of autonomous properties of units in BMS come from their ability to respond to changes in environment, primarily through performing multiple operations. Also, a unit may have self-regulation through enzymatic actions. The regulation among the group may be endowed in objects similar to enzymes or hormones (this aspect is discussed in the next sub-section). In the case of holons and holarchy, the autonomy is endowed as the ability to manage the inter-dependence in the external environment. Also, the internal environment acts like a closure where a set of holons share the interactions and modify their decisions. Here, the historical process may fix the canons while letting the holons use flexible strategies to deal with contingencies. A change in the set of canons used may take place over time through network level learning. The fractals, by setting of goals along with vitality measures that monitor and act on the environment, may have a high level of autonomy. The autonomy of a group is in the negotiation of goals that are essentially similar. The fractals may contemplate regrouping in response to changes in the vitality measures.

In summary, the design of the fractal and its dynamic evolution can be an all-encompassing task that includes technical, human and cultural dimensions, that can lead to self-governing units. Whereas, HMS takes a more technically oriented approach. Only elements which can be precisely designed are included. All the knowledge is assumed to be explicit and to be incorporated in the system. Design of Bionic Manufacturing is realised through genesis. This has the flexibility to evolve different forms according to the needs of the system (the design requirements of life).

5.3 Operational Features

Operational features of manufacturing systems exhibit functional inter-dependence among units: both hierarchical and heterarchical. This is captured by the various flows and efforts in coordination to ensure harmony in operation. Especially, in the absence of centralised control of unity of command, there is the possibility of chaotic behaviour as the autonomous units pursue their own actions.

In order to ensure harmony, regulatory mechanisms for control and coordination are called for. Regulatory mechanisms are those whereby the various activities of the component parts of the organism are modified so that they contribute to the coherent functioning of the organism as a whole.

However, the regulation provided by these mechanisms may vary depending on whether it is for short or long term coordination. For instance, a typical short term regulation such as changes to production quantity may be communicated and acted upon immediately. Whereas, long term regulation such as lowering of inventory levels or reduction in production cycle times or even improving employee satisfaction may involve analysis accompanied by modification of practices. This type of regulation may need wider consultation and may not be immediate.

Now, consider the above characteristics along with the type of mechanisms. The mechanism may be global or filtered through hierarchical whole-part relations (i.e, regulation between adjacent layers) and/or local (among units of a 2-level hierarchy). Further, the definition of regulation may be

Concept	Type of Regulation		Type of Mechanism			Definition of Mechanism	
	Short term	Long term	Global	Hierarchical	Local	Pre-defined	Adaptation
BMS	Enzymatic action, CNS	Hormones	CNS	Enzyme, Hormones	Enzymatic action	Enzymes, Hormones, CNS	?
FF	Fractal navigation, JIT, Kanban	Vitality measures of environment	No	Goal coordination	Goal, JIT, Kanban	JIT, Kanban	On goals
HMS	Coordinators	No	No	Plan coordination	CN	CN	RL of coordination

JIT: Just in time, CNS: Central nervous system, CN: Contract-net,, RL: Reinforcement learning

Table 1: Comparison of Regulatory Mechanisms

completely pre-defined or left to be adapted. Where regulation relies on adaptation, the units may take responsibility, but questions such as when and how to regulate is largely left to learning and reinforcement processes within the units.

A detailed comparison of the operational features is given in Table 1. From this it can be seen that all the concepts promote unity of action through flexible forms of coordination in both hierarchical and lateral directions. In BMS, the existence of hormonal and enzymatic actions promote commonality of functional goals between cells and other hierarchical layers. In addition, a system of coordination similar to the central nervous system (CNS) may be envisaged (this aspect is not really considered by BMS). Features of the FF include: global goals, goal formation and inheritance through coordination with a subsidiary fractal (i.e., a super-ordinate fractal). However, short term coordination may be augmented through Kanban and JIT type systems. In HMS, coarse plans (process plans and schedules) are specified which are progressively refined by lower level holons. However, the purpose of hierarchical coordination is to integrate the actions of lower level units, rather than a form of command and control. Further, in HMS an adaptive type of coordination mechanism along with contract net protocol is suggested.

6. CONCLUSION

The concepts of Bionic, Fractal and Holonic manufacturing are unified in proposing distributed, autonomous and adaptive systems. Specifically, the concepts advocate structures of manufacturing systems that are less rigid, and are more amenable to be dynamically reconfigured. An important observation coming from these concepts is the need for continual assessment of the organisation in light of the contingencies in the environment, such assessment being undertaken by the cooperating operational entities to permit dynamic restructuring.

On particular aspects, the following can be observed:

- Applicability and development of basic concepts: The analogy of biological systems provide BMS with a stronger set of concepts to draw from. For FF and HMS, further effort may be required to develop the design and operational concepts of manufacturing.
- Difference in development focus: Fractal factory emphasises the role of environment, both business and human, in developing a responsive and flexible manufacturing system. Whereas, the others seem to focus on the technology end to provide flexible and intelligent forms of automation of devices and equipment.
- Difference in level of autonomy: Autonomy of fractals can be extended to be self-governing. HMS and BMS, at present, are more concerned with the operational aspects of autonomy, i.e., execution and control of processes both at the individual and community levels.
- Design approaches and methodologies: The approach to design varies with FF advocating a bottom-up process and functions to subsume those already assigned. The others define a top-down specification.
- Operational mechanisms: These can range from simple and fixed regulation to those that permit adaptive approaches to deal with changes in the environment. The types of mechanisms supported can be local or hierarchical. However, BMSs can be designed to have global mechanisms similar to the nervous systems.
- Applications: Applications of these concepts are mixed with FF leading in reported industrial applications. However, HMS is also advanced in developing concepts and approaches to design that can be put into practice. BMS has been taken up by IMS/NGMS along with FF, but reports on industrial applications have not been evident in the literature.

Finally, while there has been some success of industrial demonstration of Fractal Factory concepts, such demonstrations are limited for the others. To this end, the research undertaken by all of the consortia may profit from extending their respective foci. However, the consortia may mutually benefit in complementing each other, in particular, with respect to the scope of human-centred manufacturing systems and technologies.

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