FRACTAL AUTOMATION – A PROPOSED IMPLEMENTATION MODEL

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ABSTRACT

Organizations face fluctuations in product demand, rapidly changing product mixes, and a need to incorporate new process innovation quickly. Agile manufacturing solutions are needed to adapt to this dynamic environment. Warnecke[1] introduced the "The Fractal Company" to address these challenges. This paper proposes an implementation that builds on Warnecke's concepts called "Fractal Automation". It addresses the challenge through control system design, mechanical system agility and system user behaviour. Firstly, the model simplifies software complexity by modularizing control systems into resources, products and transport. Secondly, agile mechanical systems are applied with flexible product routing, resources (or stations) that are modular and easily moved, and increased process flexibility built into the resources. Thirdly, the model relies on system user behavior to achieve the fractal objectives that are costly to attain programmatically. With an agile platform and access to data, system users are empowered to achieve fractal objectives of self-similarity, self-organization, self-optimization, goal-orientation and dynamics. This model enhances flexibility, scalability, and adaptability. The capital cost of the automation is higher but the total cost of ownership is lower to achieve agile manufacturing. This delivers productivity gains and competitive advantage.

Keywords: *Modular, Flexible, Scalable Automation, Agile Manufacturing, Fractal Factory*

1. INTRODUCTION

This paper proposes a model for the implementation of "Fractal Automation" based on Warnecke's 1993 theories of the "Fractal Factory". Emerging concepts that have been proposed in literature are reviewed that respond to the need in organizations for more agile manufacturing solutions. The positioning of "Fractal Automation", relative to other forms of automation, is identified to highlight where the concept has benefits. The proposed model is described in detail and applied to a typical automation system including evaluation criteria, connections to fractal theory and implementation risks. Fractal theories have many conceptual advantages and this paper proposes a model that can be applied to a practical implementation.

2. PROBLEM STATEMENT

Organizations are facing global fluctuations in the demand for products, the need to adapt to rapidly changing product mixes, and the ability to easily incorporate new manufacturing process innovation. Conventional automation has rigid, hierarchical structures, which are optimized to the original system design specifications. While these systems perform to the original design criteria extremely well, they do not adapt well to the changing needs identified above that many organizations are facing. Adapting to a dynamic environment requires significant downtime and access to specialized experts that are often not resident in the manufacturing firm. Organizations that are facing these challenges require a new manufacturing paradigm.

3. LITERATURE REVIEW

The notion of fractal manufacturing was first introduced by Warnecke in his book "The Fractal Company" in 1993. A fractal is defined as "an independently acting corporate entity whose goals and performance can be precisely described" Warnecke [1, p137]. In addition to this fractal definition, Warnecke defined the essential features of fractal entities to include self-similarity, self-organization, self-optimization, goal-orientation and dynamics.

Other comparable concepts that have emerged in the literature include "Holonic" and "Bionic" manufacturing as a result of organizations continually striving for increased operational and structural flexibility. As a comparison, "Holons" are autonomous, cooperative entities that are defined by their functions or tasks to be done. As a result, holons are suited for "self-managing units with limited capabilities for self-design or self-governing" Tharumarajah, et al. [2, p328]. Bionic manufacturing draws parallels with cells in bionic systems. The cells are similar but have unique functions and are capable of multiple operations. Similar to holonic systems, bionic systems are focused on selfmanaging. Fractal based systems, on the other hand, "promote continuous adaptation to changes in the business and operational environment. Consequently, fractals may be seen as dynamic with the ability to reconfigure themselves in response to the environment." Tharumarajah, et al. [2, p328]. Fractals, therefore, could be designed to be a selfgoverning entity. Another comparison made by Tharumarajah, et al. [2], is that holonic and bionic solutions focus more on the technology to make the devices display the autonomous behaviour. This focus could lead to concentration on the automation and the neglect of human and business elements during design. The elements of the Fractal Factory can be found in organizations today but "these do not contain the full solution as more work is required to coordinate the actions of the individual fractals and put in place mechanisms that permit self-organization and dynamic restructuring" Tharumarajah, et al. [2, p326].

The pursuit of more agile manufacturing solutions has led to a series of models based on intelligent agents. For example Leitão & Restivo [3], propose a holonic manufacturing control system called "ADACOR". Zhang & Anosike [4], developed a multi-agent solution called "DIMS" that generates optimal and timely responses to changes in the environment. Alsafi & Vyatkin [5], propose a novel approach to achieving fast reconfiguration of modular manufacturing systems, based on an ontology-base reconfiguration agent. Tang & Wong [6], propose a multi-agent system for manufacturing control that provides high robustness, good response and expandability. Ryu & Jung [7], propose an agent based fractal manufacturing system referred to as "FrMS" based on a basic fractal unit "BFU". They acknowledge that fractal manufacturing has many conceptual advantages but implementations have been known to be difficult. Their work studies the basic components with an eye toward future implementation. The proposed solutions, based on intelligent agents, incorporate complex software technologies that have barriers to implementation in current automation solutions. This paper proposes a model that does not rely on intelligent agents or inference engines to avoid these barriers in current industrial automation but it does not preclude their application in future extensions. An intelligent agent based solution, such as the examples above, could be incorporated.

Another area covered in the literature concerns the optimization of plant layouts. Saad & Lassila [8], evaluated layout design in fractal organizations. They found that it is generally possible to reduce material travelling distance by increasing the degree of optimization of the plant layout for a specific product mix. However, layout design in a constantly changing agile environment is different because optimizations may be short lived. "Therefore, in the long run, random machine placement may be as good as detailed material flow analysis" Saad & Lassila [8, p3548]. This concept of flexible machine placement is applied in the proposed model in this paper.

4. THE OPPORTUNITY

The fractal factory, as proposed by Warnecke [1], has many conceptual advantages to help an organization adapt to a rapidly changing environment. That being said, the fractal objectives of self-similarity, self-organization, selfoptimization, goal-orientation, and dynamics are challenging to implement programmatically given the current available automation technologies. A viable solution could be one that i) removes the barriers caused by rigid, hierarchical controls architectures, ii) introduces more inherent flexibility in the mechanical system, iii) provides the operators relevant information and iv) empowers the operators to make decisions and achieve the fractal objectives.

The positioning of current forms of automation is shown in Figure 1. "*Hard-tooled, continuous"* machines have many mechanical linkages and minimal reliance on control software. These machines are highly dedicated to perform specific tasks and have minimal programmability or intelligence. They are not easy to re-configure or re-design as any change requires new custom tooling. These systems operate at high throughputs and are typically used with high volume, low mix products that don't change over time. "*Standard product integration"* is a system comprised of a number of standard products integrated together. These are positioned low on flexibility because one is limited to the functionality built into the standard product. This form of automation also assumes that standard products are commercially available to perform the required operations which may not be this case for emerging technologies. "*Custom turnkey automation"* is an optimized solution that performs the original system design specifications extremely well. Any machine configurations that are built into the system are very convenient for operators. Adding or modifying the core functionality of these systems requires high expertise and significant downtime. These solutions cover a relatively wide range on the chart overlapping the other forms of automation. "*Manual lean cells"* are standalone machines that are typically loaded and unloaded manually. Flexibility, modularity and scalability are high as these machines can easily be moved, re-designed and re-deployed for alternate purposes. Production throughput is low due to manual load/unload. The targeted positioning of Fractal Automation is shown in Figure 1. Flexibility, modularity and scalability are high which aligns with the fractal objectives. Production throughput, while not as high as hard-tooled continuous machines, can be comparable to the other forms of automation.

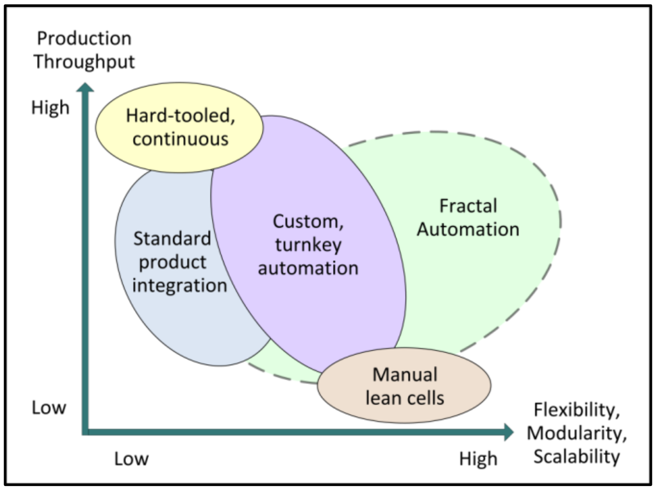

Figure 1. Fractal Automation positioning relative to alternatives

5. EVALUATION CRITERIA

Table 1 lists the key criteria in evaluating the effectiveness of a given manufacturing solution in achieving the objectives of fractal automation.

Table 1. Fractal Automation criteria

Criteria	Benefit
1. Flexibility	Easily reconfigure the system to run new products or run existing products alternate ways.
2. Modularity	Easily swap processes, introduce improved processes, support plug & play resources.
3. Scalability	Increase or decrease production capacity to adapt to changing demand. Shift capacity globally.
4. Adaptability	When a disturbance occurs in the environment, the system can adapt and recover quickly.
5. Cost effective	Lowest "total cost of ownership" (even if system capital cost is higher)

6. PROPOSED FRACTAL AUTOMATION MODEL

Fractal Automation addresses the identified challenges from three angles which include control system architecture, mechanical system agility and system user behaviour:

1. Control System Architecture – Modularize the conventional hierarchical controls architecture into key functional areas that support fractal automation.
2. Mechanical System Agility – Incorporate flexible conveyance systems and modular station concepts that support fractal automation.
3. System User Behaviour – Provide system users with the agile platforms, relevant data, and training required. Then empower them to play a key role in the fractal automation solution.

6.1 Control System Architecture

Traditional manufacturing control systems are centralized applications that are developed and adapted on a case-by-case basis. They tend to have rigid hierarchical structures that require significant effort to implement, maintain, and reconfigure [3]. While this approach may be adequate for stable, mature products, it is not suited for rapidly hanging environments. These control applications do not cope efficiently when there is a need for increased flexibility and agility in manufacturing systems. It usually takes a well trained expert and significant downtime to make changes outside of the originally programmed configurability.

To overcome these constraints, the proposed model breaks down these hierarchal control structures that are static and inflexible, into modular building blocks that facilitate the implementation of fractal automation. This model proposes breaking the controls architecture up into 1) Resources, 2) Products and 3) Transport as shown in Figure 2. Each module operates independently with well defined interfaces. The separation of these elements accommodates the proposed criteria through abstraction, encapsulation and inherent modularity. This in turn greatly simplifies the implementation of fractal automation.

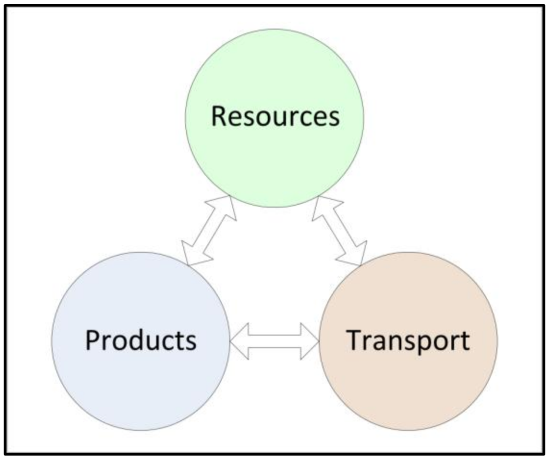

Figure 2. Fractal model control modules

The modularization of key system functions has support in other models. For example, Zhang & Anosike [4] observed that manufacturing systems, like most natural systems are structured hierarchically. In their proposed model, "products to be manufactured are also modelled using hierarchies of agents in accordance with the actual structure of the products.

This enables interactions amongst resources and products to occur in a natural and recursive manner." Zhang & Anosike [4, p870] As another example, Tang & Wong [6, p89] propose an architecture where system control is separated into i) robot control, ii) material handling and iii) supervisory control of other subordinate agents.

6.1.1 Control System Architecture – Resources

The machines within a plant that perform the manufacturing and assembly processes on products are referred to as "*resources*". Automation resources are typically structured in a hierarchy. For example, a given plant could have multiple assembly lines, each comprised of multiple zones, with each zone containing multiple cells and each cell containing multiple stations. In the proposed model, each of these resources would be a fractal so the plant would be comprised of a multi-level structure of fractals.

Resource fractals are autonomous entities dedicated to providing services. They have standardized interfaces and offer plug & play functionality for ease of flexibility and scalability. Resource fractals decide what services (or automation processes) they can offer and focus exclusively on providing these on demand. When a new resource is plugged into a system, it gets recognized and its services become available. Table 2 provides example attributes for a typical "resource fractal".

Table 2. Attributes of a "Resource Fractal"

Controls Architecture – Sample "Resource" Attributes	
Goals	• Maximize quality (i.e., yield), availability (i.e., uptime), efficiency (i.e., actual speed relative to expected).
Operations	• Perform requested services based on provided process parameters. • Notification when service is complete with data results.
Configurations	• Physical location – such as position on a conveyor, GPS location. • Transport connections – all the possible ways products can be transported to the fractal such as pallet stop on a conveyor, AGV stop, manual operator route, etc. • Parent child relationships of the fractal within the resource hierarchy. • Unique machine identifier. • Definition and descriptions of services offered.
Live data	

6.1.2 Control System Architecture – Products

This control system module deals with the handling of "*products*" that are manufactured and assembled by automated systems. Products are comprised of a hierarchy of components and assemblies. Each major product assembly would be handled as a fractal with the finished deliverable product being comprised of a multi-level structure of fractals.

Product fractals manage all of the data and procedures required to manufacture assemblies that get combined to form the final deliverable. In traditional systems, product control is integrated throughout the machine control application which makes flexibility, modularity and scalability a challenge. By separating product control into an autonomous entity, the desired criteria are easier to achieve. By building product fractals on configurable data, it becomes convenient to make changes to the product mix. Table 3 provides example attributes for a typical "product fractal".

Table 3. Attributes of a "Product Fractal"

Controls Architecture – Sample "Product" Attributes	
Goals	• All required processes completed successfully. • Achieve the expected overall cycle time. • Maintain and manage the required product data.
Operations	• On last operation complete, determine the next resource to route to and process steps required. Request transport to the next resource fractal.
Configurations	• Processes to be performed, rules and parameters. • Parent child relationships of the fractal in the product hierarchy.
Live data	• Location or status of products (in progress, in queue, completed). • Operations that are completed, quality & production data. • Processes remaining.

6.1.3 Control System Architecture – Transport

A factory has multiple means of transporting product. As examples, product can be conveyed in pallets, moved by an operator, travel with an automated guided vehicle (AGV), transported by a moving robot, travel in a tote or tray, etc. In the proposed model, the "*transport*" software module handles the transportation of product between resources. Each material transport system is considered to be a fractal. A factory then has a number of "transport fractals", that when combined, make up the complete product transportation solution. Transport fractals manage all data and logistics required to move products from their current physical location to a new desired location. In traditional systems, transport control is integrated throughout the machine control application which makes flexibility, modularity and scalability a challenge. By separating transport control into an autonomous, configurable entity, it is easier to adapt to rapid line layout changes. Performance optimization also becomes easier to manage within independent transport fractals. Table 4 provides example attributes for a typical "transport fractal".

Table 4. Attributes of a "Transport Fractal"

Controls Architecture – Sample "Transport" Attributes	
Goals	• Maximize throughput by keeping all bottlenecks stuffed and balancing the remaining utilization. • Minimize work in progress (WIP).
Operations	• Find the optimal path to go from A to B (could cross fractals). • On request to move, controls the transport. If path spans other fractals, hand-off to next transport fractals en route.
Configurations	• All available transport connections (factory scope).
Live data	• Location of product. • Size of queues.

6.2 Mechanical System Agility

For Fractal Automation to succeed, the mechanical systems need to be made flexible, modular and scalable. Traditional systems place processes in a dedicated, serial order that follows the assembly process. Changing the order of operations or swapping out processes tend to be costly, time consuming and a barrier for factory personal to perform.

The proposed model relies on a high level of flexibility and modularity to be incorporated into the mechanical system up front. Robots should be used wherever practical as they offer high flexibility. Similarly, servo motors and servo pneumatics should be used where practical for added flexibility. Product routing should be flexible to enable transport between multiple resources as opposed to a single fixed order. As examples, RMT Robotics offer an intelligent automatic guided vehicle called "ADAM" that dynamically chooses its route adapting to any environment. The ADAM transport vehicle "steers clear of obstacles, whether they're expected or not, independently plotting the best path to its destination". See http://www.adam-i-agv.com/ As another example, ATS Automation Tooling Systems Inc. offers a flexible linear motor based conveyor system called the SuperTrak®. Each pallet on the SuperTrak® conveyor is independently controlled with its own programmable speed, acceleration and precise stopping locations. Carriers can route to any stopping location on the system as required by the assembly process without fixed tooling required. See http://www.atsautomation.com/ These example products provide flexibility that is conducive to fractal automation.

To accommodate modularity, it must be convenient to remove or add stations without taking the line down for extended periods of time. The plant personal must be capable of making these swaps without requiring specialized expertise that is not available to them. To accomplish this, all mechanical and electrical interfaces must be easily disconnected, reconnected and tooling realigned. Modularity supports scalability as resources can easily be added or removed. In addition to this, the system must allow new resources to be added at any step in the process without having to reconfigure the whole line. This is challenging with fixed, serial layouts but becomes possible with flexible layouts. So for true scalability, plant personal can add or remove resources (i.e., production capacity) to any operations that have become the constraining bottleneck in order to achieve the production goals of a product fractal. "failure modes and effects analysis (FMEA)" to identify the highest potential failure modes and incorporate the ability to adapt to these. For example, a complicated assembly process, performed by a single resource that does not have a redundant backup is higher risk. Having a manual bypass option readily available would help mitigate the risks if the critical resource went hard down.

6.3 System User Behaviour

Employees play an important role in the application of fractal theories. Warnecke highlights this with the notion that instead of treating people as a disruptive factor to be eliminated through automation, in the fractal factory they are bearers of hope [1, p178]. Employee's roles and responsibilities will increase in scope since "the Fractal Factory requires human design intervention at all levels" [1, p189]. Employees must dominate the manufacturing process because "focusing on technology-dominated structures does not itself offer a guarantee of success" [1, p192]. Workers are more than mere operators in the process. "They must be turned into plant leaders requiring the appropriate training and qualifications" Warnecke [1, p195].

The proposed model relies on the concept of empowering employees to play an integral role in the fractal automation. Warnecke reiterates that data must be made available throughout the whole company for employees to contribute to fractal goals. Employees also require the latitude to apply the methods they deem appropriate under the circumstances. This enables self-organization and aligns with the fractal concept that internal methods can vary. Warnecke [1, p144] acknowledges that "since setting priorities for complex situations is a subjective matter, problems must be solved, and action must be taken when they arise". The proposed model relies on empowering people to make these subjective decisions as opposed to implementing them programmatically in software.

In the proposed model, employees formulate the fractal goals in a dynamic process that serves the objectives of the broader company goals. Employees also take responsibility to coordinate goals amongst fractals. For example, even if it is in a fractals best interest to finish a given set of operations, it could be in the company's best interest to suspend this task and share resources. Employees need the data to understand these trade-offs and the tools to act. In summary, this model relies on system users to make informed decisions to achieve self-organization, self-optimization and goal-orientation.

7. PRIOR SUCCESS WITH FRACTAL CRITERIA

An example where an industry leveraged elements of the desired criteria occurred with automation for "anti-lock brake systems (ABS)" the mid 1990's. The ABS technology was evolving quickly, suppliers had to provide a range of product variants to customers, and demand fluctuated rapidly. Flexibility was required to support the many product variants and minimize customer specific tooling. Not all versions of the product went through the same sequence, or even the same number of assembly operations [9, p11]. Scalability was required to be able to respond to rapid changes in demand. These ABS manufacturing systems had modular stations that contained flexible robots wherever feasible. The conveyor was configured to automatically route pallets to the right set of workstations. If a station was busy, the pallet would be re-routed to optimize throughput. If any one process failed, other operations would continue working (i.e., adapt to disturbances). These systems had significant engineering challenges. "For example, in writing the computer software that would manage the entire process, it was necessary to anticipate all of the possible modes of failure and variations in the process" Pisano and Rossi [9, p11]. These ABS manufacturing systems demonstrate success with flexibility, modularity, scalability and adaptability. They were centralized, hierarchical systems that offered a high level of agility designed in up front. While highly flexible, it took specific expertise and significant downtime to extend these systems beyond the original level of agility initially built in. Plant personal were constrained in how much they could extend system agility, later in the systems life cycle. This proposed Fractal Automation model could be a valuable enhancement to the successful developments that occurred in ABS manufacturing.

8. APPLYING THE MODEL – SAMPLE AUTOMATION SYSTEM

Figure 3 shows a 2D layout of a hypothetical automation system that assembles a mobile device such as a cell phone.

The assembly processes include:

1. Loading a plastic base to a pallet
2. Keypad assembly and insertion
3. Assembly and insertion of inner housing
4. Assembly of electronics (processor board, camera, GPS, etc)
5. Installation of the battery
6. Installation of LCD display
7. Load plastic cover
8. Laser weld the cover
9. Final test and unload to trays

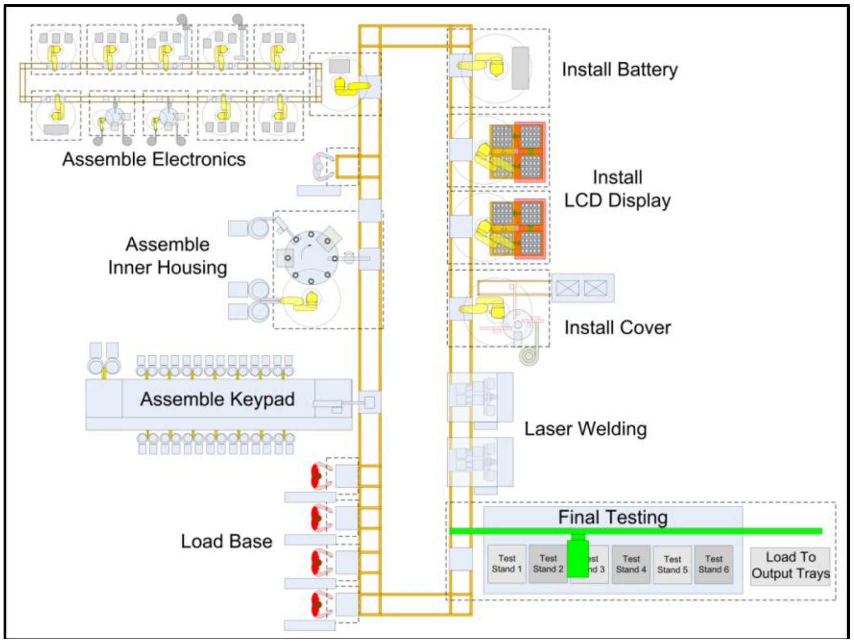

Figure 3. Conventional Line

The processes occur in a fixed, serial, order. Control of the main conveyor and pallets is centralized in a single machine controller. Individual cells have distributed controllers but are logically tightly coupled to the main line controller. The architecture is hierarchal and optimized to meet the original system requirements. Known product configurations at the time of initial system design have been incorporated and are convenient to operate.

Figure 4 shows an alternate layout of the system reconfigured to better meet the fractal automation criteria. The processes are no longer arranged in a fixed, serial, assembly order. Additional conveyor lanes have been added to allow pallets to travel directly from any station to any other station. Pallets travelling on the outside conveyors will queue up in front of processing stations. Pallets travelling on the inner two conveyors can bypass these queues to get to their target destination. This flexible routing enables the system to perform process steps in any order. The operators have intentionally been located in the centre of the system on both sides of the line. All operators have interface terminals with extensive data conveniently made available. The operators have a direct sightline to all of the machines to be able to easily view and monitor status. Machines requiring more frequent part loading are positioned closer to operators. The improvements to the evaluation criteria are considered below.

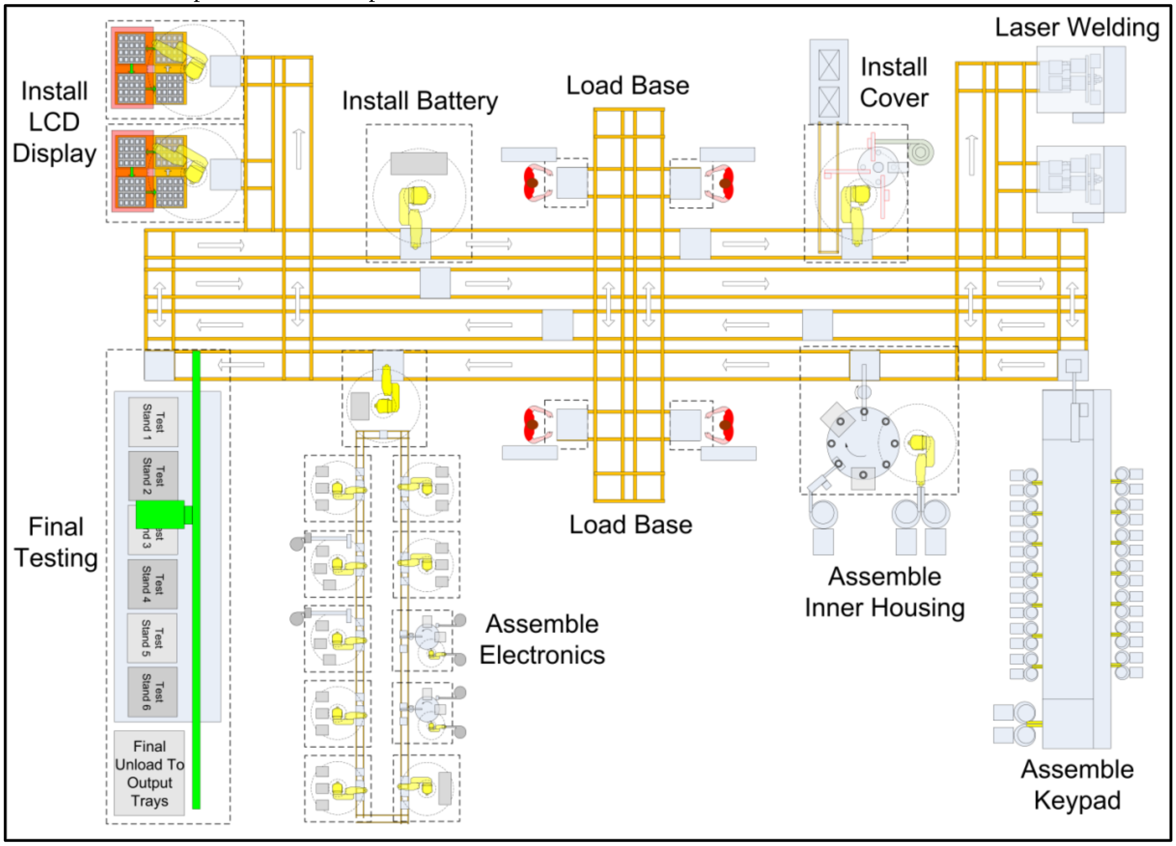

Figure 4. Reconfigured Line (Flexible, Modular, Scalable, and Adaptable)

8.1 Flexibility

The ability to route pallets from any station to any other station offers a high level of flexibility. It enables a flexible sequence of operations for any given product. New products, with unique routing, can be easily added. Having "Product" control independent of "Resource" and "Transport" control supports this well.

8.2 Modularity

The machine resources in Figure 4 are designed with plug and play functionality. A resource can be plugged into the system, the resource can be made available for products to be routed to it, and the resource can start to perform manufacturing services without specialized programming required. Having "Resource" control independent of "Transport" and "Product" control supports this well.

8.3 Scalability

The large arrows in Figure 5 show different ways the system can be scaled up or down in multiple directions. The main conveyor can be extended right or left, the smaller side conveyors can be extended, the number of operators can be modified. The fact that the machine doesn't follow a serial fixed order allows resources to be inserted anywhere and get utilized. Having "Transport" control independent of "Resource" and "Product" control supports this well.

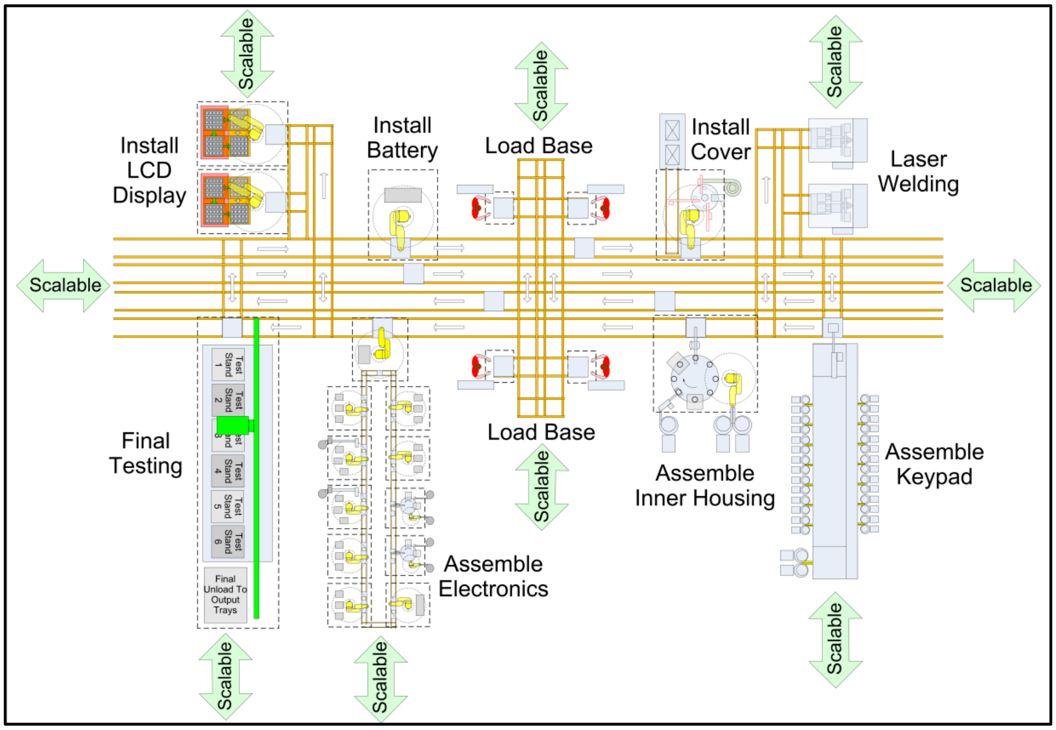

Figure 5. Scalability

8.4 Adaptability

The flexible pallet routing in Figure 4, combined with the fact that the operators can quickly adjust the routing, enables the system to respond to disruptions quickly. For example, if a machine went down, the operators could immediately change routing to another machine or back to an operator on that step for manual processing. The fact that operators are positioned centrally and have tools and data made available, enables them to respond to environmental disruptions quickly and effectively.

8.5 Cost

A system built with Fractal Automation principles will have a higher machine capital cost. As an example, the conveyor (including pallets that are not all shown) in Figure 3 would represent roughly 5% of the total system cost. The conveyor in Figure 4 would be roughly 2 times this conveyor cost. The machine control software for Figure 3 would represent roughly 8% of the total system cost. The software for Figure 4, which supports the increased flexibility and scalability, would be 1.5 times this software cost. The cost of the stations in Figure 4 would have an added 5% overall system cost to make them plug and play with added process flexibility. Overall, the capital cost for the system in Figure 4 would be roughly 14% higher than the cost of the system in Figure 3. Thus the benefits realized from the added flexibility, modularity and scalability must offset this 14% increase in capital cost when considering the total cost of ownership. The ability to get new products to market faster, to respond quickly to changing market demand, to bring new process innovations online quickly, and other benefits need to offset the increased capital cost to make Fractal Automation cost competitive. This is conceivable in environments that demand rapid change and agility.

9. ALIGNMENT WITH FRACTAL THEORY

The previous section highlighted how the reconfigured system in Figure 4 improves on the evaluation criteria. This section connects how it achieves the fractal objectives.

9.1 Self-similarity

Resource fractals, as shown in Figure 6, are a cluster of machines with operator(s) that perform assembly processes as a service. In the example, resource fractals have pallets arriving with products to be operated on. Many also have components that get loaded into bulk feeders or trays. Resource fractals have similar inputs and outputs but operate differently internally and require different support structures. For example, variations within the resource fractals in

Figure 6 that require unique competencies include i) robotics, ii) lasers, iii) electronic assembly, iv) test instrumentation and, v) dedicated mechanical systems. Self-similarity permits such deviations enabling fractals to have unique internal structures [1, p140].
Transport fractals provide the service of taking an object in a current location and transporting it to a desired future location. From a system perspective, transport fractals operate on similar inputs and outputs but they will be structured very differently internally. They will incorporate different modes of transportation (such as a conveyor or AGV) and will have unique configurations such as shown in the difference between Figure 3 and Figure 4.

Product fractals provide the service of handling the manufacturing process and creating finished goods. Product fractals would have similar inputs and outputs from a system level but would be structured differently internally to produce a varied product mix. All three of the fractal types described above consists of a hierarchy of fractals incorporating patterns within patterns.

9.2 Self-organization
The alternate model, shown in Figure 4, enables operators to apply suitable methods to optimize the organizational processes and procedures. For example, the operators are empowered to move machines around, add or remove machines, redefine the sequence of operations, configure what processes are automated verses manual, etc. Operators can implement continuous improvement ideas and get direct and immediate results. Operators have the ability to restructure, regenerate and dissolve the fractals they belong to.

9.3 Self-optimization
The increased level of flexibility, modularity, scalability and adaptability in the Figure 4 layout, provides pportunity for self-optimization. For example, the system could indicate where the bottleneck is at any time and its conceivable the bottleneck could shift based on the product mix in production at the time. The operator is enabled to make changes with Fractal Automation to i) ensure the bottleneck is always stuffed to maximise throughput, or ii) add capacity to remove the current bottleneck and increase throughput (in which case the bottleneck shifts to the next slowest process). As another example, Figure 4 includes combinations of flexible robotic cells and dedicated mechanical machines. The user could have optimizations available that combine higher volume, dedicated production with lower volume, specialized production. In summary, by providing the operator relevant data to work with and an agile system platform, they are enabled to perform self-optimization within Fractal Automation.

9.4 Goal-orientation
In Figure 4, operators have been intentionally moved to the center of the line on both sides to be integrated into fractals. They have been provided extensive, live performance data and have been empowered to formulate their fractal goals. Warnecke [1, p165] reinforces that goals should not be imposed but "it seems to be more appropriate to generate them in a process of coordination between the participating fractals and to modify them as necessary". It is conceivable that the fractals shown in Figure 6, with the advantages of the proposed model, could accomplish this coordination and serve the objectives of higher level goals. The important aspect of this example is that the operators are integral to the goal-formation process. The model will accommodate expert systems or intelligent agents but does not rely solely on them. The operators are provided the data, methods and freedom to restructure, regenerate and dissolve fractals to achieve the goals.

9.5 Dynamics and vitality
The system in Figure 4 provides a high level of flexibility in the routing of products and sequence of operations. If there is a problem on the line, the operators could easily route product to an alternate resource to perform the operation. If an alternate resource is not available, they can route that process step to a manual station instead. The level of agility proposed in the system enables operators the ability to act successfully under changing environmental influences. Warnecke [1, p149], states that "fractals should be formed in such a way that relationships (flow of material, staff and information) within the fractal are stronger than those to the outside". It is conceivable that this would be the case with the fractals shown in Figure 6.

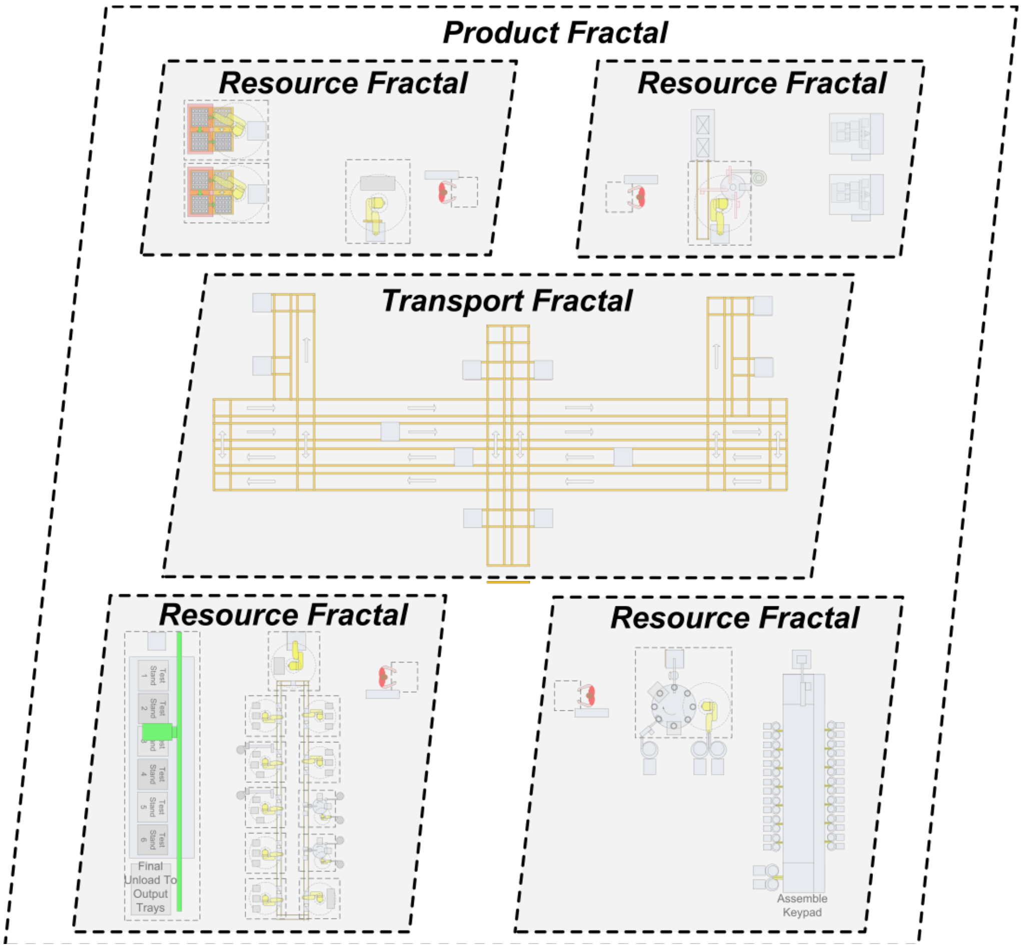

Figure 6. Fractals

10. APPLICATION SCOPE

The Fractal Automation model adds value when a company is dealing with unknowns they are unable to plan for up front. Example unknowns include global demand, variability in demand across a product mix, advancing process innovation and/or rapidly evolving products. The sample applications in this paper included fast-evolving products in the automotive and electronics industries. The model could be applied to any industry with high volume manufacturing such as solar, medical device, and wide range of consumer products. The model is less applicable to low volume, stable products.

A factory primarily staffed with workers (instead of robotics) is highly adaptable to process changes. However, with high volumes, this requires many people, large floorspace and achieving high quality is costly. An agile, automated system becomes an advantage when production reaches millions of parts per year.

11. IMPLEMENTATION RISKS

The key implementation risks with the Fractal Automation model include cost, controls latency and software complexity. These risks and their mitigation are described below.

11.1 Cost

A system designed with Fractal Automation principles has a higher machine capital cost. That being said, a true cost analysis goes beyond the base machine cost to the total cost of ownership. The benefits of Fractal Automation, such as being able to rapidly run new products, introduce new processes, scale to new demands, adapt to disturbances, etc. must deliver a lower overall "total cost of ownership". The risk is that companies will not be able to perform an accurate total cost analysis or short term thinking will be a barrier.

11.2 Latency

Typical automation systems make state change decisions in the tenths of a millisecond. These latencies drop below 10 milliseconds in high performance systems. Latency is the time it takes between a sensory input event occurring in the environment until the next operation or action is commanded. The implementation of Fractal Automation introduces added software processing with the risk that these latencies become significant. Proper system design and testing are required to ensure latencies do not have a detrimental impact.

11.3 Software complexity

The proposed implementations to date have high software complexity. The non-recurring development costs to progress these frameworks into production are prohibitive. Many suggested models rely on intelligent agents or inference engines that are challenging to implement on today's industrial controls products. There is also often a barrier to adoption of advanced software methodologies on the plant floor. System users that support and maintain automation demand hardware and software solutions they are familiar with. This proposed model attempts to simplify the software architecture through the resource, product, transport fractals and the reliance on operators for complex decision making. It still involves added complexity that could be a barrier.

12. CONCLUSIONS

This paper proposes a model for the implementation of Fractal Automation that enables organizations to increase manufacturing agility. The model proposes the modularization of conventional, centralized, control software architectures into three key elements i) resources, ii) products and ii) transport. By encapsulating and abstracting these key elements, the level of complexity in achieving fractal objectives becomes manageable.

The model also proposes changes to the approach to physical systems to achieve fractal objectives. Transport systems must accommodate flexible product routing to move away from the paradigm of fixed, serial processing. The automation stations require modularity to enable plug and play functionality and have increased operational flexibility built in. Applying these mechanical and controls concepts enhances a systems flexibility, modularity, scalability, and adaptability and provides a viable platform for Fractal Automation. The capital cost of the automation is higher but the total cost of ownership is lower in situations where the advantages of agile manufacturing are able to deliver productivity gains and competitive advantage. System users are the last key piece of the proposed model. When users are provided an agile system platform, access to extensive relevant data and the necessary training, they are enabled to achieve the fractal objectives of self-similarity, self-organization, self-optimization, goal-orientation and dynamics. Achieving all of these objectives programmatically is a barrier but by enabling users with the platform and empowering them, the objectives of Fractal Automation become plausible. For further study, these concepts would be applied to a real world automation system.

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