Title

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Conceptualization of Cultural Diversity for Efficient and Flexible Manufacturing Systems of the Future

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Abstract

Manufacturing systems of the future need to have flexible resources and flexible routing to produce extremely personalized products, even of lot size equal to one. In this paper we have proposed a framework, which is designed to achieve this goal. Towards this we have integrated an established cultural evolution model to achieve desirable flexibility of resources and acceptable routing time. Promising results are evidenced through a simple proof-of-concept agent-based simulation. The simulation results reveal that the products need to move less in more diversified cultural groups when looking for suitable resources. It was also observed that the more time we provide for cultural dissemination, the cultural groups become increasingly coherent due to homophily. For scenarios, which require diversification of resources, we need to find a balance between coherence and diversification. This paper provides first insights into these aspects for a production shop floor.

Keywords: Industry 4.0; resource flexibility; routing flexibility; personalized production; cultural dissemination; group coherence.

Introduction

The industrial manufacturing paradigm has already evolved from mass production to mass customization. Fueled by initiatives like Industry 4.0 (Lee, Bagheri, & Kao, 2015), we foresee a further improvement in coming years, namely the paradigm of personalized production. Personalized production targets an extremely flexible manufacturing system which could respond to predicted and unpredicted changes in the production environment and allows customers to create and design themselves (Hu, 2013; Mourtzis & Doukas, 2014). Manufacturing systems supporting personalized production should exhibit the following features (Ogunsakin, Mehandjiev, & Marín, 2018):

- Resource Flexibility: flexibility of processing stations (or machines) to make multiple parts, which means that one processing station is not designated for one task and can perform different tasks as required.
- Routing Flexibility: flexibility to execute same operation (or function related to a task) using multiple processing stations, which means that a single task can be performed by many processing stations.
- Lot Size Flexibility: ability to produce a very small customized and/or personalized lot size in a non-batch mode, which is a direct consequence of at least (if not any other dimension) the above two features.

The progress towards a truly flexible manufacturing system (FMS) is naturally driven by technological needs from industrial process management viewpoint, which falls into general knowledge areas of scheduling (Wang, Zhong, Dai, & Huang, 2016; Marichelvam, Prabaharan, & Yang, 2014), resource optimization (Ogunsakin et al., 2018; Beruvides, 2017), constraint satisfaction (Ezpeleta, Colom, & Martinez, 1995), and related.

Still, the body of work considering the aspect of "personalization" is quite lean and requires further attention. Realizing this, several projects and activities are already under progress. One significant effort endeavours to develop cognitive products and production systems incorporating *human-like* capabilities like "perception, understanding, interpretation, memorizing and learning, reasoning, planning and hence cognition-based acting" (Pro2Future, n.d.). The project is about complex cognitive modalities of humans, products and machines and their interrelationships. In this paper, we argue that one does not need to have high-level cognitive capabilities to be effective. At a scale of a population or a group, a very basic level cognition of interacting agents may result in a desirable global situation. We just need to find the conditions in which this may happen.

Agent-based modeling (ABM) (Bonabeau, 2002) is a method used for modeling such inquiries. One particular area of interest of a production unit is the layout of shop floor which should be optimized for maximum gain in productivity, particularly in case of FMSs. This case study is adopted in our paper. At a conceptual level, a group of agents comprising an interactive social network is augmented with the notion of culture to ground them with the physical world.

Most optimization mechanisms (as stated above) either consider a mathematical abstraction or imitate a real-world situation as their manufacturing environment (which is mostly *static*) while modeling, and then proposing a solution within these presumptions. A more recent work (Ogunsakin et al., 2018) also considers mobile processing stations as a mean to achieve flexibility of shop floors. The idea is to make resources available as and where these are required. Although, this approach addresses the challenge of routing flexibility to an extent, the capabilities of resources still remain static.

In our research, we are mostly focusing on resource flexibility, which means that the processing units are able to dynamically change their *capabilities* and therefore a resource is able to perform several tasks. The goal is to keep resources stationary (and avoid expensive process of mobility) and arrange resources in groups of *complementing* capabilities. Ideally, a resource would designate itself for a capability that would optimize the manufacturing process in several dimensions, such as production rate, lead-time per order and reactivity index (Ogunsakin et al., 2018). However, we only focus on resource availability and mobility of products.

We postulate that flexibility in resources, routing and personalizing relate to evolution of culture as it emerges at the physical level due to local interactions of *mostly* stationary individuals. In the context of resources (processing units) of a production shop floor, we seek for groups of *complementing* capabilities, self-organizing to produce an approximately optimized layout for the products, which ensures availability of resources and reduces products' mobility. This novel idea would provide an entirely new perspective for the future research in this domain.

In the next section, formal definition of culture and cultural diversification is presented; followed by detailed description of the methods. Next, we present details about our model and simulation; followed by discussion on initial findings. We end the paper with an elaborate outlook of future work.

Culture, Diversification and FMS

A culture is a multi feature system evolving in time. One characteristic of culture is its coherence when seen from outside. Definitely, this coherence results due to a majority of people trying to acquire a similar behavior (often termed as a trait) in a certain context (often termed as a feature).

Relating these concepts to FMS, we need to conceptualize features and traits of resources and products, where a resource is a processing unit in the production line, whereas a product is obviously a product under production. Although a product can also be considered as a cultural entity, it is not the case for the purpose of this paper. Only a resource is a cultural entity.

Resources are flexible, initially having some randomly chosen features and a randomly chosen trait against a feature. For example, a processing unit may have ability to perform one, two or more tasks T_1, T_2, ... with certain levels of precision P_1, P_2, ... Here, a tuple consisting of n values is a set describing capabilities of a resource. For example, the set $\{P_2, P_1, P_3\}$ can be interpreted as: this resource can perform task 1 with precision 2, task 2 with precision 1 and task 3 with precision 3. Furthermore, it cannot perform any other task.

Further, all products have a *sequential* list of capability requirements. For example, a product with set $\{P_1, P_1, P_2\}$ requires task 1 with precision 1, followed by task 2 with precision 1, finally followed by task 2 with precision 2. The question is: would cultural diversification be able to generate a physical layout that would ensure availability of capable resources with minimal mobility for all the products in the system? Technically, what are conditions which lead us to an acceptable (and approximate) solution of the problem?

Such a scheme is naturally compatible with the requirement of a flexible manufacturing system stated above, namely, flexibility in resources, routing and personalizing. Axelrod provides evidence in his seminal work (Axelrod, 1997) for such a simple configuration of cultural descriptions which can result into a locally coherent, but globally polarized culture as a consequence of localized interactions of participating entities.

Our intuition is that unbounded coherence between cultural groups would not help in this scenario. The reason is that limitless coherence has no control over where the boundaries of the global polarization would occur, which is not compatible with a system which seeks for economy of resources and optimizations in several dimensions. That is the reason, we try to find conditions which end up in approximately acceptable structuring in terms of coherence (termed as limited coherence) vs. polarization. To achieve this, we have taken motivation from Centola et. al's work (Centola, Gonzalez-Avella, Eguiluz, & San Miguel, 2007) in which a random drift is used to deviate a highly coherent environment. This drift is achieved through change in the neighborhood of an agent. Theoretically it is possible to do it, however in scenarios like FMS it is not practical as we cannot move processing units so frequently after deployment. Hence, we have fine tuned Axelrod's model of cultural dissemination (Axelrod, 1997) with focus on limited coherence between cultural groups and tried to find out how much we can achieve and in which conditions. Definitely, at run time, the dynamics of requirements and products may change and make a particular layout extremely inefficient. To address it, a further investigation is required, which is planned for the future.

Methods

Axelrod's Model of Cultural Dissemination

Axelrod's model (Axelrod, 1997) thrived for cultural homogeneity (Bednar, Bramson, Jones-Rooy, & Page, 2010), where adjacent cultures get influence from each other. The model is based on cultural components defined by three factors: features, traits and persons. A culture has many features, such as habits of eating, recreation and leisure. These features may not be identical across different cultures. Each of these features have several traits, which may differ across cultures. A person is a placeholder of a culture described by one of f features and t traits. Axelrod proposed a model seeking for cultural homogeneity proclaiming that different cultures are destined to cohere together so that they appear as a cultural unity, but at the same time, there exists a clear-cut differentiation between cultures.

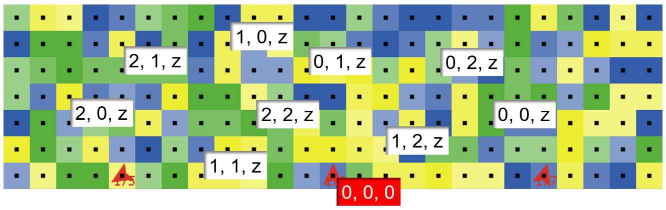


Figure 1: Initial distribution of a 25 × 7 grid constituted by blocks of culture (anchored on central black persons); each block is a tuple of 3, representing three features (green, blue, yellow) of three traits each (3 shades of a color). Each cell's color has a meaning; for example, all green cells have capability to perform task 1 with precision value 0, which is followed by precision values of task 2 (0, 1 or 2); last value is not path dependent and represented by z. Possible combinations of colors are shown with values; each tuple relating to a person on the top-left corner. A product has a unique sequence of task to perform represented with an arrow shape (at the bottom center of the space).

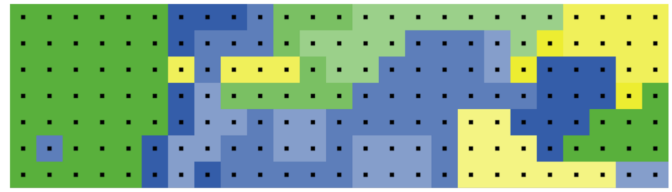
Axelrod model was able to demonstrate that the above two (rather contradictory) goals can be achieved by a simple interaction model (realized through N coordination games) between neighboring persons. Axelrod showed that N coordination games are necessary for a broader scale evolution of a culture. Furthermore, groups' consistency across different aspects of societal norms makes a group culturally coherent and different from others.

We developed a simple simulation model for demonstration purposes using NetLogo (Tisue & Wilensky, 2004). Figure 1 presents a grid of 25 × 7 cells. Each cell is represented by a person (in black) and the corresponding culture acquired, depicted by cell color of the cell the person is occupying.

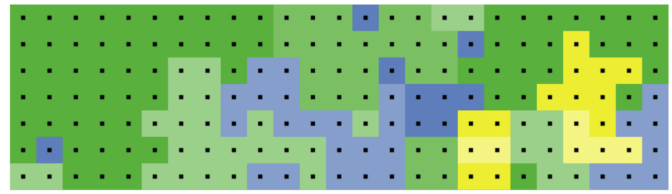
Axelrod's model calculated similarity s between neighboring cultures (based on Von Neumann's neighborhood). If s is not 1 (100%), with a probability p, the value of a $different$ column of a person is replaced by the corresponding value of the neighboring person. This simple mechanism is able to generate clusters of coherent cultures as shown in Figure 2. If we define **diversity index** as the mean diversification of cultures of all persons when compared to their neighbors, the Axelrod model would converge into a single culture most of the time with diversity index equal to 0. This is not desirable in the context in which we want to use this model. Therefore, the model was extended as detailed in the following.

Model Motivation: Constrained, N-Coordination Games for Cultural Diversity

Before describing the model, we will emphasize the scenario given in Figure 1. Given that a processing unit is able to perform three possible tasks with three possible precision values,



(a) Axelrod Model: diversity index = 0.34 at 10000th iteration



(b) Axelrod Model: diversity index = 0.25 at 20000th iteration

Figure 2: Axelrod's Model: Evolution of cultures shown in Figure 1. (a) at simulation iteration 10000 showing clusters of cultures starting to form. (b) at simulation iteration 20000 showing further consolidation of clusters of cultures. The evolution is destined to end up in very few cultures (1 or 2).

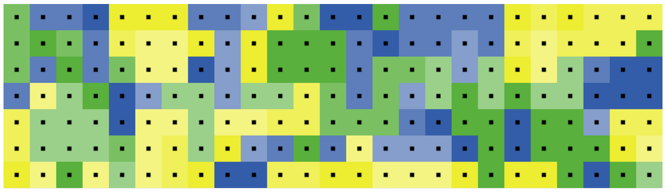
we can see a clear capability matching through colors. Furthermore, a product is introduced which need to complete a sequence of three tasks offered by different resources. We hypothesize that using the constraint, N coordination games, we can achieve cultural diversity closer to what is desirable. This would directly impact products' traversing efforts in a positive way.

The Proposed Diversity Dissemination Mechanism

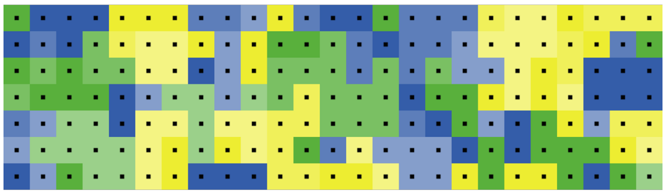
The Axelrod model is too skewed towards coherence and would end up in too few cultures. Hence we propose to refine the Axelrod model in the following way. Axelrod model seeked for similarity s between neighboring cultures. If s is not 1 (100%), with a probability p, the value of a $different$ column of a culture is replaced by corresponding value of the neighboring culture. We extend this model by applying an extra constraint. That is, the replacement is only possible if s is also less than a threshold th, which is for now given a static value of 0.5. This obviously increases the overall *diversity_index* of the system as shown in Figure 3. Before analyzing the impact of this refinement we explain the mechanism of product traversing.

Traversing Mechanism

All products have a sequence of tasks to perform in the form [x, y, z]. A product first gets the value x, and maps it onto resources with identical capability and residing close to its position. Let's denote the resource with r. After visiting r, the product seeks for the next nearest resource corresponding to y. It is assumed that y has a relationship with x. This means that, in terms of colors, this cell (and the resource residing on top of it) should have the same color. The last task z is independent and just show the range of flexibility that the system



(a) Proposed Model: diversity index = 0.50 at 10000th iteration



(b) Proposed Model: diversity index = 0.44 at 20000th iteration

Figure 3: Proposed Model: cultural diversity at iteration (a) iteration 10000 and (b) 20000.

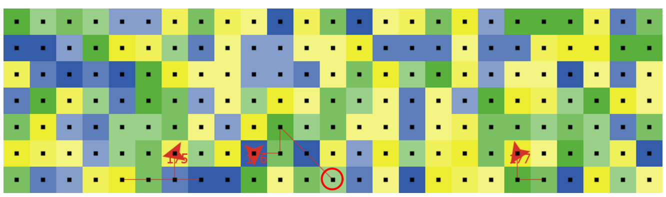


Figure 4: Traversing behavior in random configuration of resource capability.

may have.

An Example Walk-through on Random Configuration (without applying diversification mechanism): Referring to Figure 4, each resource (black agent at the center of a cell) is randomly populated with vector [x y z], where x, y and z may have three possible values 0, 1 and 2. Products have to perform three tasks in a sequence. One product (at the center) has to perform task 1 with precision 0, task 2 with precision 1 and task 3 with precision 1. It starts at the position marked with red circle. First it performs task 1 with precision 0. That takes it 2 steps to the top left cell, which has the nearest resource with this capability. Next, it has to perform task 2 with precision 1. The nearest resource, which has first column equal to 0 (assuming a connection between task 1 and 2) and second column equal to 1 is the resource at the bottom; hence the product would move there. Next task is task 3 with precision 1. Assuming that it is an independent task, the product would try to find the nearest resource that has the third column equal to 1 (any color). This can be any resource (cell at the left is selected). Hence, the **mobility index** of this product is 4, the total number of hops traversed. The other two products also traverse to complete their tasks. The average mobility index turns out to be 3.94.

It seems that random configurations would be the best, but this cannot be the case in a structured environment, particularly in case of an assembly line type of manufacturing.

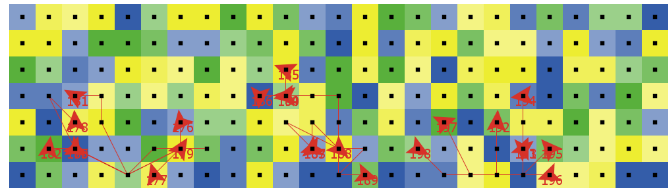
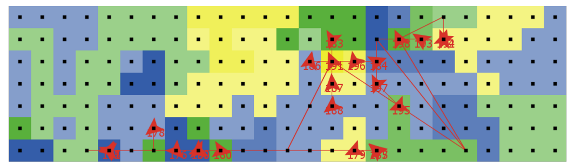
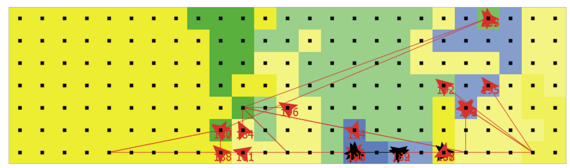


Figure 5: Traversing behavior in random Layout without diversification applied.



(a) Axelrod Model (10000th iteration): diversity index = 0.34, mobility index = 6.78



(b) Axelrod Model (20000th iteration): diversity index = 0.24, mobility index = 8.66

Figure 6: Traversing behavior in Axelrod's Model.

Analysis of Initial Findings

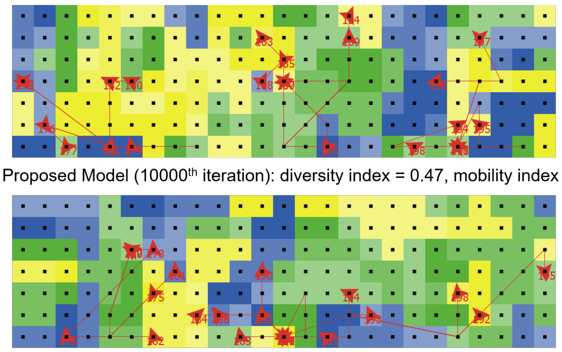
Definitely, the introduction of th retains diversity index in case of extension of Axelrod's model. This helps in task completion capability of the system. This claim can be verified by analyzing the mobility of products and the diversity index in three cases. We have used 25 products distributed at three places. In each case, the simulation was run for 100 times and the results were averaged. In the following, we present a sample visualization for each case which is close to average values, at two sampling points (iteration 10000 and iteration 20000) if applicable.

Random Layout

In Figure 5, the system has a diversity index equal to 0.70 and a mobility index equal to 3.4. This is also confirmed by the graphs shown in Figure 8 (diversity index) and Figure 9 (mobility index). As we mentioned already, random configuration is most flexible and would always be best in its task completion capability. However, this configuration is unrealistic. In reality, we need to plan placement of resources and deploy them accordingly.

Axelrod's Model

In case of Axelrod's model, we have analyzed the results for diversification period of 10000 and 20000 iterations. These two situations are represented in Figure 6. With increasing polarization and decreasing diversity index, the average mobility index drops. After running the simulation for 100 runs and averaging, it was observed (see Figure 8 (diversity index) and Figure 9 (mobility index)) that mobility index is just less



(a) Proposed Model (10000th iteration): diversity index = 0.47, mobility index = 5.00

(b) Proposed Model (20000th iteration): diversity index = 0.24, mobility index = 8.66

Figure 7: Traversing behavior in proposed Model.

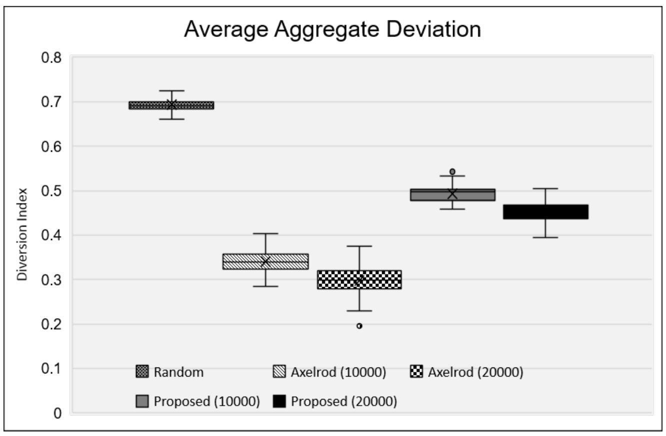


Figure 8: Graph showing diversity index of 100 simulations runs.

than 8 (diversity index = 0.35) in case the diversification happens for 10000 iteration, whereas, mobility index is slightly higher than 8 (diversity index = 0.30) in case the diversification happens for 20000 iteration. As shown in Figure 6, this decrease is due to nonavailability of resources indicated by products turning into black color.

Proposed Model

Lastly, the proposed model solves the above issue. We can see a smooth performance of tasks for all the products, which is evident from Figure 7. Again, we have analyzed the results for diversification period of 10000 and 20000 iterations. These two situations are represented in Figure 7. After running the simulation for 100 runs and averaging, it was observed (see Figure 8 (diversity index) and Figure 9 (mobility index)) that mobility index is equal to 4.57 (diversity index = 0.49) in case the diversification happens for 10000 iteration, whereas, mobility index is about 5 (diversity index = 0.45) in case the diversification happens for 20000 iteration.

Comparative Analysis

As diversity decreases, the availability of resources becomes more difficult. In this particular scenario, the products need

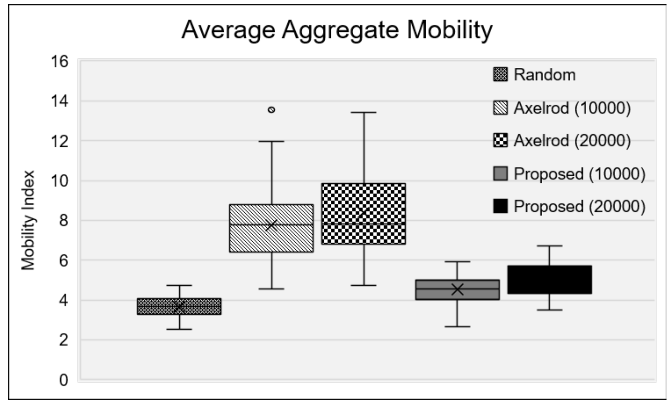


Figure 9: Graph showing mobility index of 100 simulations runs.

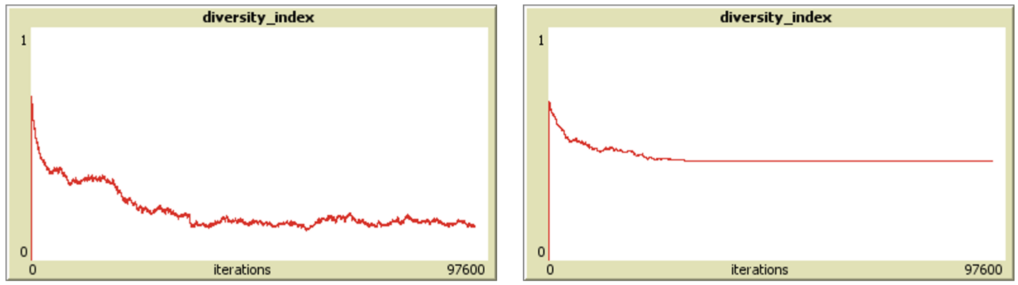
to move less in more diversified cultural groups. The ideal case is random layout in which the products need to move the least. As diversity decreases from random layout to Axelrod's model, the mobility increases substantially. In case of Axelrod's model, it was also observed that the more time we provide for cultural dissemination, the cultural groups become increasingly coherent. In the simulation world's geometry used, the number of culture clusters goes down to a few if the number of iterations is increased to 100000. Obviously, this is not an interesting case to show. However, in the case of the proposed model, this does not happen with such high intensity. In fact, the diversity index never drops below 0.4 and interestingly it reaches an equilibrium in most runs. Hence, it is possible to provide a drift against unbounded homophily effect resulting into an extremely low diversification by using a simple threshold based control mechanism. The graphs shown in Figure 10 validate our claim.

Conclusion and Outlook

Manufacturing systems of the future need to have flexible resources and routing to produce extremely personalized product, even of lot size equal to one. What we have seen is that flexible manufacturing systems can be realized without moving the resources (processing units) by enabling reconfiguration of capabilities of resources based on dissemination of culture concept proposed by Axelrod. However, the Axelrod model has a focus on coherence of cultural groups, which most of the times ends up in one or very few cultures. If we equate such an instance of a culture with a single capability of a resource, we are left with extremely limited resources and products cannot complete their production life cycle.

Hence, we proposed to have a constrained cultural coherence mechanism by introducing a threshold. This tiny development has a significant impact on the increase in diversity of the culture along with related resources being in close vicinity to each other on average. This not only ensured an increase in resource availability as a whole, but also managed to decrease the mobility of products in search of suitable resources.

However, the real contribution of the paper is integration of



(a) Axelrod's Model

(b) Proposed Model

Figure 10: Comparative Analysis of diversity index: Axelrod's Model vs. Proposed Model.

manufacturing processes with cultural considerations, which naturally fits into the problem. In our view this is a novel approach of real significance. However, the work reported in this paper is just a proof-of-concept. We need to have more thorough experiments to measure the efficiency of the model in challenging environments such as environments having inflow and outflow points, more in-depth capabilities and richer relationships between tasks.

In the next phase of the project, we will induct models of dynamics, which include timing of tasks, conflict and deadlock resolution between products seeking for identical resources, and more realistic analytics such as production rate, lead-time per order and reactivity index. Lastly, we would also include an autonomous learning system, which would help resources learn and change their configurations on the fly based on product types, requirements and trajectories.

Acknowledgment

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