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TOWARDS A DIGITAL DEPOT TO SUPPORT SUSTAINABLE MANUFACTURING DURING CRISIS RESPONSE

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ABSTRACT

The COVID-19 pandemic has imposed new challenges to maintaining sustainability in our manufacturing operations. With such high variability in demand for urgently needed products (e.g., personal protective equipment, testing technologies) and shifts in the needed capabilities of already complex production systems, sustainability challenges concerning waste management, life cycle impact characterization, and production operations have come to light. An extensive amount of data can be extracted from manufacturing systems, but it is not yet being used to improve the performance of production systems and maintain sustainability strategies during times of distress. This article proposes the concept of a Digital Depot. Being virtual in nature, the depot can contain plans and data for many different types of crises and contain a wider array of products than would be available in a physical, national stockpile. The information could be made available on demand to a national base of manufacturers to help them swiftly pivot to the production of critically needed goods while building on their existing manufacturing capabilities. The contents of the Digital Depot would be applicable to several stages pertinent to manufacturing operations including product definition, production planning information, asset and factory-level data, as well as data concerning the supply chain, distribution, and end-of-life stages. Future work is recommended in the development of templates for robust and secure data sharing, as well as multi-disciplinary identification of businesses cases for data-driven collaborative and sustainable manufacturing practices enabled by the Digital Depot.

Keywords: Smart Manufacturing; Manufacturing Ecosystem; Supply Chain; Sustainable Manufacturing; Resiliency; Digitization; National Stockpile; Manufacturing on Demand; Life Cycle Assessment; Life Cycle Inventory

1. INTRODUCTION

The COVID-19 pandemic ushered in new challenges for the manufacturing industry including sharp rises and steep declines in consumer demand while coping with a volatile supply chain [1–3]. Reactions to these changes happened swiftly— a necessity in an effort to maintain human life. Nonetheless, such variability in demand requires exceptional agility and resources to allow manufacturers to swiftly pivot to the production of critical goods. Without the right practices and key engineering artifacts in place, the outcome could naturally lead to waste (in a variety of forms such as time and materials) and augment the negative impact that society and the manufacturing sector has on our environment. The COVID-19 pandemic highlighted that improvements were indeed needed to the collection and maintenance of our nation's emergency response stockpiles, which was further emphasized by President Joseph Biden Jr.'s Executive Order for more resilient supply chains [4].

An Atlantic article cites Health and Human Services Secretary Alex Azar as reporting the stockpile contained only 42 million face masks when 3.5 billion of these masks were needed [5]. The

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article raises two shortcomings: the understocking of the stockpile and the onerous regulations on the production of supplies. Supplying a nation of over 331 million people on short notice would be no small feat, not to mention the demand of 7.8 billion people across the globe. Manufacturers have recognized this challenge as they have shifted their prioritization of Industry 4.0 objectives towards agility in operations and flexibility in the customization of products since the onset of the pandemic [6]. Furthermore, sidestepping regulations on this type of equipment that is meant to protect human health and safety would come with risks. Technical solutions that can help speed the testing and certification of products are needed.

In this paper, the concept of a Digital Depot is proposed to help address any forthcoming emergency response needs. Under this concept, product designs and manufacturing instructions can be stored along with methods for vetting suppliers that will be able to create new products on demand in response to emergency needs. In addition, sustainability aspects of the mass production of new products can be assessed and planned for before production begins. The Digital Depot can build on current trends in manufacturing including advanced assessment and planning for environmental impacts, manufacturing-as-a-service, digital certification of production, and virtual training for manufacturing and maintaining unique products. The Digital Depot offers an opportunity to reduce physical stockpiles of fully assembled products, and instead allows for a pivot towards 'stockpiling data' and raw materials, which could be used to produce a variety of relevant products during specific crisis situations. In this paper, we describe the concept of a Digital Depot in light of these trends and discuss how the approach can be used to reduce environmental risks for future large-scale response efforts. A policy component would need to be developed to fully deploy the technical capabilities outlined.

2. INCORPORATING SUSTAINABILITY INTO THE DIGITAL DEPOT

A Digital Depot would consist of a comprehensive set of planning tools focused on producing the goods that are needed to respond to national crises. Being virtual in nature, the depot can contain plans and data for many different types of crises and contain a wider array of products than would be available in a physical stockpile. The key concept is that these plans could be made available on demand to a national base of manufacturers to help them to swiftly pivot to manufacture new types of goods building on their existing manufacturing capabilities. Data for the Digital Depot can be acquired from existing databases and systems already being utilized by many manufacturers (e.g., Enterprise Resource Planning [ERP], Materials Resource Planning [MRP], Certified Reference Materials [CRM]) through the development of a digital thread for the critical products necessary for crisis response. By taking the time for advanced planning we should be able to anticipate more scenarios for production. Considerations from the basic supplies that may be needed to physical stockpiles of appropriate raw materials to end-of-life plans for rapidly surging products can be incorporated into plans.

In Diaz-Elsayed et al. [2], the authors identified three key risk areas for unanticipated consequences of the rapid pivoting to new products and supply chains that could have negative impacts on our environment and workforce:

- **New modes of operation for manufacturing**: The vast majority of job functions under COVID-imposed conditions have shifted. Many jobs, particularly in the manufacturing sector, pivoted to remote work when possible [7]. Functions from management and manufacturing engineering to training and maintenance all found a remarkable capacity for remote work. Others operated under alternative and extended schedules in order to limit the number of people on site at any given time.
- **Life cycle impacts of new and fluctuating product streams**: The environmental impacts of manufacturing products are highly dependent on the material inputs and manufacturing processes. The complexity of assessing life cycle environmental impacts using current methods means that these assessments are not readily available during planning phases of product design and production. In addition, supply chain disruptions can also result in poor material or inefficient process choices. The result will be poor balancing of benefits with environmental impacts.
- **Increases in waste generation**: Waste created by rapid changes in supply and demand during the COVID-19 pandemic sky-rocketed, and concerns for the dangers raised to the environment naturally followed [8–10]. Hospitals reported spikes in medical waste and supply chains of recycled materials destined for manufacturers were disrupted by the changing consumption patterns [11,12]. Producers of consumer and commercial goods worked hard to find different outlets for the products and pivot to different supply chains with mixed success. Dairies and other food industries reported significant waste increases of their products brought on by the supply chain disruptions [13].

This paper describes how these risk areas can be addressed by leaning on the Digital Depot concept to help quantify and plan for pending impacts.

3. WHAT IS THE DIGITAL DEPOT?

A central function of the Digital Depot would be the 'virtual stockpiling' of relevant product, production plans, and data for components and assemblies needed during potential emergencies. Rather than stockpiling the physical (manufactured) goods in advance, which may result in either overproduction or long-term decay and malfunctions of such goods, the Depot would enable rapid on-demand production by supplying relevant digital files to previously vetted manufacturers (see Figure 1). Such data, including Computer

Aided Design (CAD) and Computer Aided Manufacturing (CAM) files, would necessarily go beyond simple geometric definitions of components, and encompass 'design intent' to allow local engineering and production teams to produce each component for 'fitness in service,' rather than to simply meet the dimensions of an annotated 3D CAD file. Indeed, connecting the product design and performance (use stage) with the manufacturing processes used to create these processes is a key challenge the Digital Depot will need to address in order to yield actionable results and true resilience in light of future crisis situations. In addition, the Depot contains guidance for rapid formation of business partnerships to facilitate rapid creation of new supply chains.

The following key components of a Digital Depot will be instrumental in incorporating sustainability thinking into the overall planning for *manufacturing for crisis response*:

- List of covered products and their performance requirements
- Digital designs for the products and components
- Mapping of component and supply chains needs
- Production instructions and training materials for unique components
- Instructions for certification of products against performance requirements
- Assessment of sustainability impacts of digital designs
- Assessment of sustainability impacts of production
- Registry of vetted suppliers for product components and assemblies
- Plans for end-of-life reclamation of identified products and by-products of their production

The Digital Depot as a concept includes two types of data distinguished by their temporal criticality. Fundamentally, the Depot is a repository or registry of the plans for producing a wide array of products needed to respond to a crisis situation. However, crisis response also demands access to temporally sensitive data such as asset and supply chain capabilities and availability that can support real-time planning. This paper limits discussion to the concept of these capabilities and does not address how they might be deployed in the real world. Understandably, access to real-time data would introduce a broad set of concerns ranging from cyber security to protection of privacy and intellectual property. Similarly, a balance between top-down planning of the system versus a demand response model of implementation will be needed to optimize efficiency and encourage innovation. Likewise, the architecture of the depot need not be monolithic, but it could be a composition of independently offered services. The implementation of the Digital Depot concept would require much thought and discussion to find a suitable balance around such factors. The Digital Depot described here represents the concept as an umbrella for envisioning a future manufacturing paradigm to support crisis response.

Figure 1 illustrates the functional areas needed to support a rapid on-demand manufacturing response to changing demands under crisis in a sustainable manner. Central to that response is the Digital Depot that contains product and production information required to activate the response. Each area is described below.

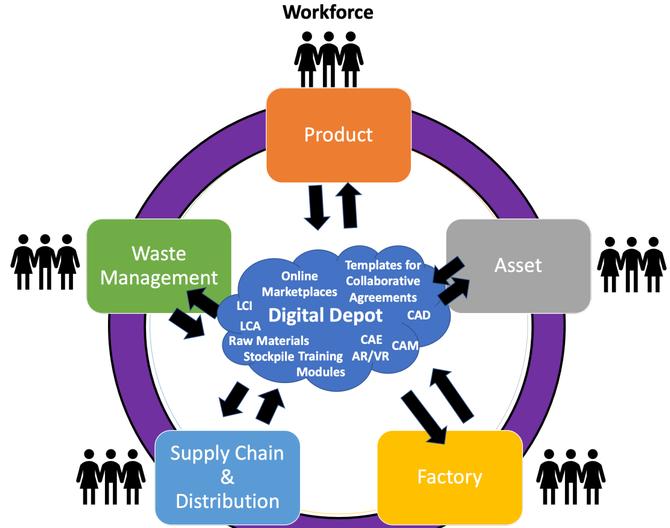

Figure 1: Examples of content that may be included in the Digital Depot with respect to production and product life cycle stages. Abbreviations: AR: Augmented Reality; CAD: Computer Aided Design; CAE: Computer Aided Engineering; CAM: Computer Aided Manufacturing; LCA: Life Cycle Assessment; LCI: Life Cycle Inventory; VR: Virtual Reality.

Product: The incorporation of product data into the Digital Depot serves two purposes. First, with advance planning of supplies, the products, materials, and production alternatives can be evaluated for their impacts across all three risk factors (waste management, life cycle impacts, and new modes of operations). Designs for the mass production of items can be pre-evaluated for life cycle properties such as material choice and waste generation. The range of products and production processes contained in the depot can include low technology items such as face masks that are needed in large quantities to very sophisticated items such as high-tech ventilators or equipment for vaccine production. By vetting the designs available, the impacts of the products in terms of waste generation and product reclamation at the end-of-life stage can be considered. Secondly, societal needs can be anticipated should the product end up being produced. We can start advance planning for the disposal systems that will be needed as well as plan for training on how the products are produced and used. In addition, virtual stockpiling mechanisms can be developed to avoid stockpiling fully assembled physical products. The Digital Depot enables rapid and agile production of such products on-demand during a crisis situation.

Asset: At the asset level, the Digital Depot can store life cycle inventory data for conventional and new products to facilitate decision-making for process planning for pending orders. Relevant life cycle inventory data for the asset include resources consumed (e.g., energy, water, materials) and are discussed further in Section 4.1. Although data analytics are outside of the scope of the functions of the Digital Depot, such services could be provided external to the depot to facilitate the sharing of production capabilities across manufacturers to expand capacity and meet large variations in demand and to propose enhanced process plans to lower the costs and environmental impacts of the asset.

Factory: At the factory level, the optimization of production operations (e.g., to reduce carbon emissions and energy consumption) can be supported by the availability of design data and real-time information. CAD files of the production equipment within a factory (existing equipment and/or planned purchases) can be used to optimize the layout of a factory and investigate strategies to reduce waste, such as wait and transportation time, in a production line. As a factory strives to improve their performance, the data acquired can support the validation of optimization strategies that have been implemented to further enable operational improvements. From a business planning perspective, the classification of a factory's digital readiness can provide management with insight about the facility's ability to adopt new digital technologies and make advancements towards their Industry 4.0 roadmap [14–16]. Additionally, a factory's plan for continuity of operations (e.g., [17]) can provide customers with insight about the facility's reliability during times of emergency.

Workforce: To support an agile and digitally-enabled workforce, the Digital Depot could provide relevant training modules (e.g., videos and digital study materials) related to specific manufacturing process and assembly tasks. For example, such materials could focus on enabling transfer learning between a given company's current workforce activities and similar, yet sufficiently different, skills required to produce a new product (e.g., a ventilator) on-demand. Instead of relying on traditional (in-person) modalities, the goal of digital workforce training modules provided through the Depot would be to allow for rapid up-skilling of the incumbent workforce. Such training would also encompass sustainability considerations, which require not just advanced technologies, but also specific workforce behaviors and skills.

Supply Chain and Distribution: A major lesson of the global pandemic has been humanity's reliance on supply chains and their rigidity in light of changing patterns of consumption. The disruption of supply chains has resulted in much waste, a significant burden on the workforce, and exceptional stress levels across society. On the flip-side technologies such as digital marketplaces enabled reconfiguration of supply chains and insights into changing consumption patterns. More pervasive use of these technologies will enable better response to future crises. Similarly, organizations that specialize in distribution, such as UPS[2], UberEats and similar services have been essential to the restructuring of supply chains and delivery to consumers Supply chains are also seeing a convergence towards leveraging shipping services [18]. The efficiency introduced through the specialization of distribution modes has the potential to result in reduced environmental impacts as the use of transportation is optimized.

Waste Management Networks: The COVID-19 impacts on waste management are only starting to be understood, but early results indicate their existence [8,10,19]. Efforts towards fostering a circular economy are growing rapidly and require much more sophisticated waste management than currently exists. An infrastructure around material identification and repurposing methods is needed. Considerations for design for remanufacturing of emergency supplies can be complimented with plans for recycling of materials through increased variety in waste management capabilities combined with specialized collection methods. In other words, digital marking of materials can help direct waste to specialized processing facilities, whether those be remanufacturing facilities or specialized material reclamation facilities. Specialized distribution networks can be established in for these purposes as well as product distribution.

Underpinning the Digital Depot are standard specifications for sharing product and manufacturing process data to be used across business partners. Standards in this area are rapidly evolving to support virtualization of manufacturing systems and services [20]. The Digital Depot will rely on the following standards for product and production systems design incorporating sustainability assessment. (This list is not exhaustive; certainly other standards will also be critical to the design and operation of a Digital Depot.)

- Product data definitions standards are now successfully deployed for sharing product designs and associated information [21,22].
- ISO 23247 is now emerging with a Digital Twin Framework for Manufacturing [23].
- Standards for measuring the sustainability impact of products [24] have been successfully used for obtaining rough estimates of impacts across a range of products, with an ever-growing number of product category definitions [25] emerging as well as more and more refined data reflecting the life cycle impacts of component materials and services.
- Standards for sustainability assessments of manufacturing processes and production systems have been recently released from ASTM International [26,27] and ISO [28,29].

[2] Identification of commercial products or services here does not imply recommendation nor endorsement by NIST, nor is it intended to imply that they are necessarily the best available for the purpose.

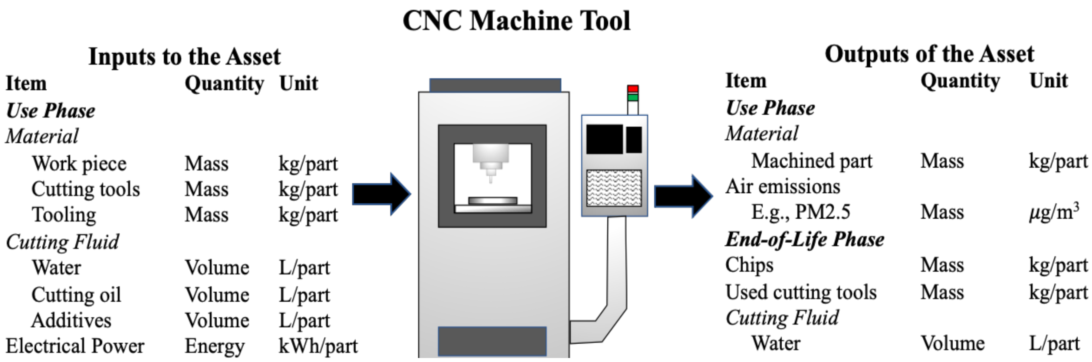

Figure 2: Examples of the types of inputs and outputs (inventory data) that would be collected for a CNC machining center for a life cycle assessment. CNC: Computer Numerical Control.

4. TRENDS IN MANUFACTURING RESEARCH TO ADDRESS SUSTAINABILITY RISKS

The framework for a Digital Depot for emergency response efforts will be a massive undertaking. Building sustainability considerations from the start is imperative to control sustainability impacts. The section highlights two key areas where today's research and development can be leveraged to address sustainability concerns in the planning effort:

- Advanced assessment and planning for environmental impacts, and
- Capabilities for manufacturing on demand.

4.1 Informing Environmental Impact Assessments

A Life Cycle Assessment (LCA) is often used to evaluate the environmental impacts (e.g., greenhouse gas [GHG] emissions) of a product, process, or system. The steps of an LCA consist of 1) Goal and Scope Definition, 2) Inventory Analysis, 3) Impact Assessment, and 4) Interpretation [24]. As the life cycle impacts of manufacturing processes vary greatly depending on category and even the model of production equipment being used, estimates of life cycle environmental impacts are expected to have significant variation and uncertainty.

The COVID-19 pandemic has introduced many challenges to the manufacturing sector, including spikes in demand for personal protective equipment (PPE) for the healthcare industry and broader public. The variation in demand for PPE has been reflected in online portals such as Project N95 and Thomas [2]. Table 1 presents Greenhouse gas (GHG) emissions for alternative types of masks. The table shows that depending on the assumptions made, the variance in GHG emissions can be significant (e.g., by modifying the type of material being used, introducing transportation impacts, or changing the number of washes for a cloth mask).

This variation in emissions generation in mask production, suggests other sustainability metrics will also vary. Similarly, but not captured here, one can expect significant variation in impacts from the type of production processes used in mask production [30] or even different design types with a single process [31].

Table 1: Greenhouse gas (GHG) emissions for the production of personal protective equipment (PPE).

Product	GHG Emissions	Notes	References
Impacts per Part			
N95 Mask	0.05 kg CO_2-eq/part (single use)	Excludes transportation; Major impact: PP material	[32]
Surgical Mask	0.059 kg CO_2-eq/part (single use)	Includes transportation; Major impact: Transportation	[8]
Cloth Mask	0.06 kg CO_2-eq/part (single use)	Excludes washing; Major impact: Cotton fabric	[32]
Cloth Mask	6.92 kg CO_2-eq/part 0.036 kg CO_2-eq/usage	Includes washing; assumes mask is used 183 times	[8]
Impacts by Filter Efficiency			
Cloth Mask	0.0072 kg CO_2-eq/filter efficiency	Assumes ~50% filter efficiency	[33]
Surgical Mask	0.0074 kg CO_2-eq/filter efficiency	Assumes ~80% filter efficiency	[33]

With respect to conducting the LCA, there are three dominant types of methods used: process, economic input-output life cycle assessment (EIO-LCA) or a hybrid approach that couples these two methods. For a process LCA, the methodology is known to be data and time intensive, which can be expensive. Nonetheless, a process LCA provides better accuracy of the life cycle environmental impacts for specific products, systems, and/or processes being evaluated when compared to the amortized impacts available for the production of products within specific industries as is done with EIO-LCA.

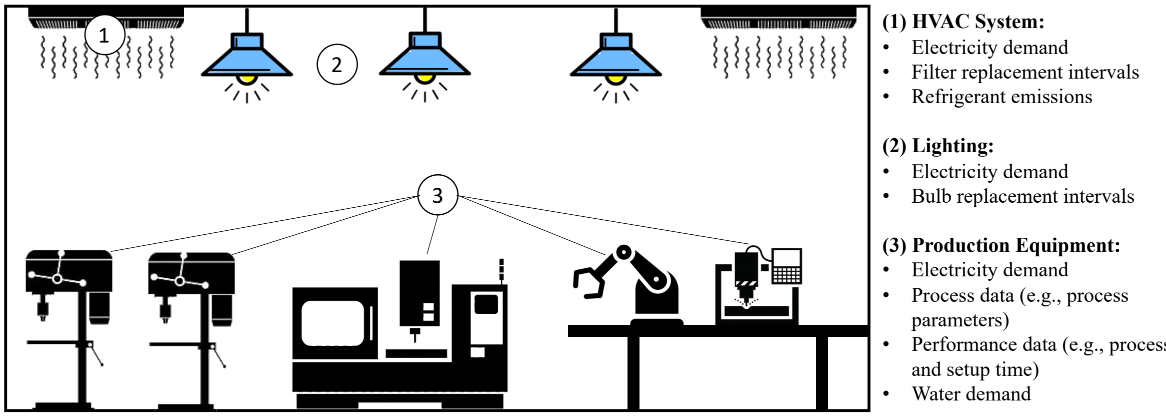

Figure 3: Factory-level information relevant to the life cycle assessment. HVAC: heating, ventilation, and air conditioning.

As a process LCA is very data intensive, the availability of data on the production floor would serve to inform the Inventory Assessment of the LCA. For example, the inputs and outputs of a machining process are depicted in Figure 2 to provide exemplary data of the type of data that would be collected for the Inventory Assessment phase of the LCA. The power demand is known to vary with time during the production of a part. Nonetheless, models have been developed to predict the energy consumed during the machining process [34]. Other relevant resources that are consumed include cutting fluids, workpiece materials, and cutting tools. While the cutting fluid consumed can be amortized over the parts produced, some process data for the LCA can be extracted from a CAD file (e.g., the weight of the material being used for the work piece).

In order to holistically obtain life cycle data for the production of a part, factory resource consumption should be considered as well [35]. Moreover, local factors, such as the climate, should be accounted for as they can influence the resources consumed by the factory [36]. Important inputs at the factory level include energy to power the lighting and heating, ventilation, and air conditioning systems and water consumption (see Figure 3). Relevant data on resource use can be extracted via conventional methods, such as utility bills. Alternative methods such as metering can provide more granular information about how the resources are consumed to more accurately attribute the resources consumed to specific production processes and parts. Meter readings could be integrated with an energy management application that stores historical data at a finer scale than what is available through a utility bill, and would grant visibility to the consumption of resources at the sub-system or asset level.

4.2 Enabling Manufacturing on Demand

The Digital Depot should contain enough information to enable manufacturing of products on demand, which is key to enabling an alternative to the current paradigm of stockpiling vast quantities of fully assembled products that may be subject to finite shelf life or experience degraded performance over time. As describe in the following section, in addition to product designs and production plans, also necessary is information on design intent, connections for integrating with enterprise and e-commerce data, cybersecurity preparedness, and support for workforce readiness.

The proposed concept of a Digital Depot is particularly powerful and relevant to the manufacturing stage for products that are complicated to produce (i.e., the majority of modern products). Even seemingly 'simple' items, such as N95 masks and replacement parts for medical equipment, contain a considerable amount of non-trivial features and manufacturing steps in their production. For example, handling and processing of filter fabric, including joining (gluing) dissimilar materials is paramount to realizing required product performance (e.g., N95 level of filtration and durability) [37]. Traditional blueprints and even modern 3D CAD drawings fail to fully describe key functional features and design intent, which may lead to unacceptable product quality. The importance of process-induced characteristics, such as machining-induced surface integrity, on functional performance cannot be overstated, and requires strong 'physics-based' understanding of unit processes [38]. Based on this realization, several efforts to include in more than just simple geometric information in the digital definition of a part have therefore been undertaken [39]. While such model-based feature identification is clearly needed to produce highly engineered components such as turbine blades and biomedical implants, the importance of this information for simpler components has become evident during the COVID-19 pandemic.

In addition to 'design intent,' we also propose that important sustainability consideration related to both production and use-stage performance be included in the 'data package' provided by the Digital Depot. Such data could include waste and environmental impact considerations, including assembly and distribution/storage information. In this manner, supply chain-wide insights regarding material, waste and energy flows could be promoted more proactively, which is envisioned as the foundation for more environmentally benign manufacturing operations.

One of the key hurdles to realizing an agile and 'real-world ready' Digital Depot lies in a 'black box' approach towards manufacturing processes that neglects the physics that govern these production steps. Manufacturing is inherently complex and multi-disciplinary, as the laws that govern even simple processes are often highly non-linear, and thus non-intuitive. By leveraging the concept of the Digital Thread and Digital Twin of manufactured components, the Digital Depot paradigm could enable agile production, while also allowing for key sustainability metrics to be considered. In contrast to traditional stockpiling and warehousing of fully assembled and manufactured goods, a Digital Depot would merely require key raw materials to be stored in limited quantities. Centrally stored digital component and assembly definitions, including material properties, manufacturing process information, and even end-of-life considerations (recoverability, reusability, recyclability) could be made available to the industrial base at short notice, in order to quickly pivot production to new product lines needed to address a crisis situation. Since the Digital Depot would embody billions of dollars of intellectual property (IP), careful consideration of cybersecurity concerns will be vital to its successful implementation.

To ensure cybersecurity and 'need to know' access to key Digital Depot information, virtual certification of participating manufacturers is proposed. Such certifications could include training and process-focused, generic 'first article' demonstration of a manufacturer's ability to effectively work with a data set provided by the Digital Depot. Since it will not be possible to anticipate every possible kind of product or component that may be required in an emergency situation, certification of manufacturers according to specific processes (filter fabric production, precision machining, etc.) would provide the scope for such first articles, within the context of initial certification. In addition to traditional manufacturing competencies, for example the ability to operate within certain quality standards (e.g., ISO 9001 [40]) and environmental standards (e.g. ISO 14000 [41]) could be required. Certification could also expand into consideration of a manufacturer's ability to capture, interpret and share relevant sustainability metrics (e.g., waste generation, energy consumption, etc.). The relevant digital competencies could be promoted through module-based online training, which could also be leveraged to ensure awareness of relevant cybersecurity standards and best practices (e.g., [42–44]).

Rather than provide a disincentive for manufacturers to participate in such certification efforts, efforts will also need to be made to ensure that the value proposition of participating in the Digital Depot program is well understood by manufacturers across the supply chain. Indeed, collaboration between traditional disconnected enterprises and industries could be promoted in anticipation of future needs to 'link' these entities in order to produce novel product lines during a crisis event. To this end, strategic networking among relevant industries and companies prior to a pandemic or similar catastrophe would be highly advantageous, and could result in significantly reduced transition and response times, were a crisis event to occur.

Across supply chains, management of access to Depot data in the event of an emergency could be carried out in accordance with previously completed certificates. For instance, a consumer appliance manufacturer with proper training and certification could gain access to ventilator manufacturing data, since the relevant manufacturing process capabilities and competencies may overlap. This data would again include digital workforce training on key manufacturing considerations such as training modules on the assembly of critical components and tuning of electronic components. Design intent of relationships between manufacturing-induced characteristics (e.g., surface finish) and functional performance in service (e.g., airflow capacity and microbial resistance) would likewise be included to support associated engineering activities.

5. SUMMARY

Disruptions in each of the life cycle stages of the product and production impact the identified risk areas for sustainability, as summarized in Table 2 and discussed in Section 2. Product designs need to account for waste generation and lifecycle impacts even under extreme duress such as imposed by emergency situations. Disruptions in the use of manufacturing assets can lead to increases in waste, impacts across the lifecycle of products especially if quality in production is compromised. Emergency impacts, such as a reduced workforce, will require rapid changes in standard modes of operations.

Table 2: Risk areas for sustainability in the context of the functional areas of production. MFG: Manufacturing.

	Sustainability Risk Areas		
Life Cycle Stages	**MFG Operational Modes**	**Waste**	**Overall Life Cycle**
Product Design		x	x
Asset Use	x	x	x
Factory Operations	x	x	x
Supply Chain & Distribution	x	x	x
Waste Management	x	x	x
Workforce	x	x	

Further impacts can be imagined for each phase and many of these impacts can be reduced through the application of digital technologies for better planning and control. Tight control over factory operations through greater use of technologies such as simulation and design can help mitigate surges in waste generation or lifecycle impacts brought on by potential declines in product. New technologies for factory operations and maintenance that involve greater use of remote capabilities can also help to reduce unanticipated sustainability impacts. Similarly, the impact in changes to operational modes could be reduced through virtual workforce training on the production needs.

The interplay of the risk factors with the identified trends in manufacturing (environmentally-informed design and manufacturing on demand in an environment of disrupted resources) produce significant opportunities for future research directions.

6. CONCLUSION

In this manuscript, the concept of a Digital Depot is proposed as a potential alternative to traditional physical stockpiles of finished goods. Rather than over-producing and stockpiling manufactured products and components that may be needed during a crisis event in anticipation of such events, a Digital Depot could offer a more resilient and sustainable alternative in the future. The incorporation of flexible and digital manufacturing technologies would support the development of the Digital Depot by facilitating access to data and enabling agile production capabilities. By virtue of being a digitally-enabled system, the Digital Depot would require significant paradigm shifts across industry in order to deliver the desired benefits. While this present work provides and technical description of the various stages of production that would be impacted by the Depot, this framework still contains significant gaps. To further develop the proposed concept, we envision convergent future work across a variety of disciplines, ranging from economics to establish clear business cases, to social and environmental studies to further define the scope and impact of environmental and societal metrics. Overall, successful transition to a more digitally-enabled future state of 21st century manufacturing will require close collaboration between a variety of stakeholders from academia, industry, government and non-profit groups. In this context, the Digital Depot could serve as a catalyst and enabler to bring together these diverse groups to realize resilient and sustainable value creation.

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