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NSF/ASME Student Design Essay Contest

Undergraduate Submission

Adaptive Manufacturing Systems: Leveraging Predictive Modeling and Cyber-Physical-Social Systems (CPSS) for Real-Time Adaptation

PROBLEM

The Design and Manufacturing Enterprise in 2040

The landscape of modern manufacturing is evolving, due to demands for greater flexibility, efficiency, and resilience. Factors such as climate change impacts on resources [1], rapid technological progress, and shifting consumer preferences are shaping systems that must quickly adapt to unexpected challenges.

As we look toward 2040, we envision the characteristics of a successful high-tech global design and manufacturing enterprise will be defined by its ability to adapt to changing market demands and unforeseen events.

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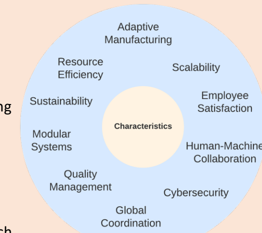
Vision for the Future of Design and Manufacturing

We envision a successful, high-tech global design and manufacturing company to be characterized by:

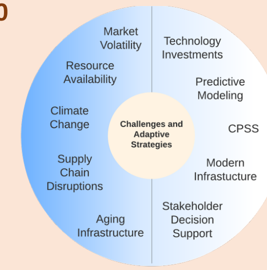
- **Flexibility and Adaptability**: Ability to adapt to changing market demands and production challenges.
- **Integration of Technology**: Ongoing use of tech including LLMs, AI/ML systems in customer-facing products and operations.
- **Sustainability**: Minimize waste, reduce energy consumption, and use sustainable materials through circular economy principles.
- **Global Coordination**: Leverage existing global networks [4] with suppliers, research bodies, tech providers, and other stakeholders.



Key Challenges in 2040

Problem

As manufacturing systems grow more complex and interconnected, the primary challenge will be ensuring operational resilience. This means production processes must be able to withstand disruptions caused by technical failures, supply chain problems, economic shifts, or natural disasters.



Proposed Method

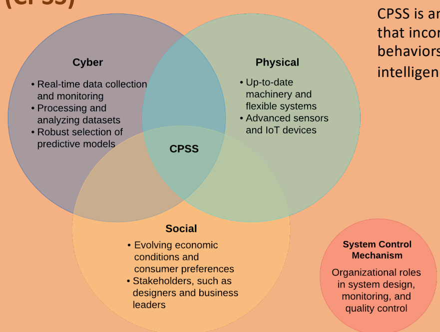
To enhance operational resilience, we propose viewing the manufacturing enterprise as a Cyber-Physical-Social System (CPSS), which will allow us to leverage predictive modeling techniques.

Problem Statement:

How can predictive modeling informed by Cyber-Physical-Social Systems (CPSS) be used to design an adaptive manufacturing system for operational resilience?

CPSS DESIGN METHOD

Adaptive Manufacturing as a Cyber-Physical-Social System (CPSS)



CPSS is an extension of Cyber-Physical Systems (CPS) that incorporates social interactions and human behaviors into the system design, enhancing its intelligence and adaptability.

- **Cyber**: Data collection, databases, communication networks, computational platforms, and predictive analytics.
- **Physical**: Modern buildings and facilities, sensors, IoT devices, and machinery capable of real-time data monitoring.
- **Social**: Economic conditions, evolving customer demand, and stakeholders such as designers and decision-makers

Using Predictive Modeling for Real-Time Adaptation

- **Predictive Maintenance**

Implementing machine learning can help predict machine failures, maintenance needs, and production bottlenecks.

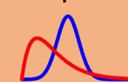
- **Production Optimization**

Applying predictive analytics to foresee changes in customer demand can optimize production schedules, resource allocation, and process parameters, allowing manufacturers to adjust operations swiftly.

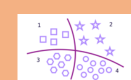
- **A Method of Continuous Learning**

An *Evolving CPSS* (E-CPSS) remains accurate and reliable through continuous updates with new data and requires setting up feedback loops that align model predictions with actual outcomes over time.

Examples



Regression task: Estimating facility energy consumption



Classification task: Classifying a product or machine part as defective or non-defective.

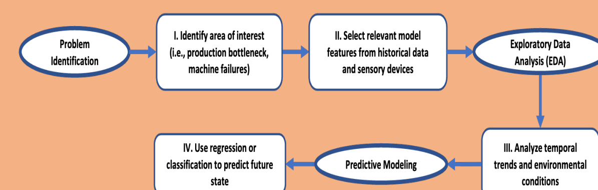
The Predictive Modeling Approach

- **Historical Data**

Use historical production data to identify patterns and trends, such as machine performance and failure rates. This data forms the foundation for building predictive models.

- **Real-Time Data**

Use sensors and IoT devices to collect real-time data on machine operations, environmental conditions, and production metrics. This data enhances accuracy by continually adding up-to-date information.



IMPLEMENTATION / CLOSURE

Example Scenario

- **Example of a Predictive and Adaptive Challenge: Anticipating Consumer Demand Fluctuations**

In a dynamic manufacturing setting, accurately predicting changes in consumer demand is crucial for operational efficiency. A Cyber-Physical-Social System (CPSS) equipped with predictive modeling can allow stakeholders to forecast shifts in consumer preferences, allowing for dynamic adjustments in production.

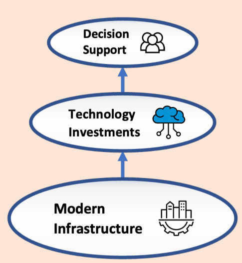
- **Mitigation Strategy: Dynamic Production Adjustment and Resource Allocation**

Cyber: Analytics platform uses market trends and economic indicators to forecast shifts in demand.

Physical: Manufacturing adjusts production lines based on cyber insights, optimizing resource use and minimizing waste.

Social: Consumer trends inform the supply chain and stakeholders' marketing strategies, enhancing decision-making and operational agility.

Steps for Implementing the Adaptive Manufacturing Enterprise



Layers of Implementation

1. **Identify Components:** Classify elements into Cyber (data analytics, IoT), Physical (machinery, infrastructure), and Social (human roles, consumer behavior) components based on requirements.
2. **Modernize Facilities:** Invest in sensors, IoT devices, and core infrastructure to facilitate real-time data collection and monitoring.
3. **Model the System**: Develop models using historical and real-time data to predict disruptions and optimize operations.
4. **Self-Adaptability:** Equip the system to reorganize resources autonomously to maintain efficacy under evolving conditions.
5. **Social Feedback and Decision-Making:** Incorporate stakeholder feedback for decision support and long-term operational resilience.

How can predictive modeling informed by Cyber-Physical-Social Systems (CPSS) be used to design an adaptive manufacturing system for operational resilience?

Closing Remarks

Through this work, we aim to equip designers and business leaders with a model to define the technological, human, and infrastructural needs for an adaptive manufacturing system, alongside its practical implementation steps.

By integrating predictive modeling and CPSS, we propose an adaptive method of enhancing operational resilience in the face of increasing complexity and uncertainty.

Broader Impacts: Education and Learning

Author's note: *"Through this work, I have thought critically about emerging challenges in manufacturing, and how to address social problems through engineering and systems design. Thinking about the broader impacts of this work has opened my eyes to a broad range of research in machine learning and computational techniques with the potential for social good, which has motivated me to undertake further studies.*

Inspired by these insights, I am pursuing an M.S. followed by a Ph.D. in computer science, with the long-term goal of contributing to teaching and research in the field."

Key References

- [1] Gavin, A., 2023, "The Future of Manufacturing: Insights from Industry Leaders on Navigating the Fourth Industrial Revolution," World Economic Forum [Online]. Available: https://www.weforum.org/agenda/2023/06/the-future-of-manufacturing-insights-from-industry- leaders-on-navigating-the-fourth-industrial-revolution/. [Accessed: 15-May-2024].
- [2] Allen, J. K., Nellippallil, A. B., Ming, Z., Milisavljevic-Syed, J., and Mistree, F., 2023, "Designing Evolving Cyber-Physical-Social Systems: Computational Research Opportunities," Journal of Computer and Information Science in Engineering, 23(060815).
- [4] Peruzzini, M., and Pellicciari, M., 2017, "A Framework to Design a Human-Centred Adaptive Manufacturing System for Aging Workers," Advanced Engineering Informatics., 33, pp. 330–349.
- [5] Steger, M. B., 2020, Globalization: A Very Short Introduction, Oxford University Press.

Acknowledgments

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