Distributed Manufacturing and Supply Chains, Applying Multi-Attribute Decision Supporting System

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Abstract

Distributed Manufacturing (DM) is a crucial interest area of operations management. That interest is rising since DM supports achieving sustainability goals, can mitigate risks of the global supply chains, and strengthen local economies. Some of these advantages and disadvantages of DM analysed earlier mainly focused on the operations. Still, there are many additional advantages across the supply chains, from local sourcing to serving the end-users and handling reverse supply chain challenges. While the economy of scale is essential in reducing costs and improving productivity, highly centralised manufacturing increases transportation costs and make operations more vulnerable and lead to supply chain disruptions by causing a ripple effect. It is a fundamental issue during the COVID-19 pandemic when government impose strict restriction on transportation. The lack of understanding of trade-offs and proper comparison of the effects could hinder the further development of DM. Increasing the confidence and reducing risks by a fair and comprehensive analysis is critical for early adopters of DM and could be the key to increased implementation. This study introduces a multi-attribute decision support system (MADSS) and an assessment process to consider the impacts across the supply chains and guide stakeholders, academics, and decision-makers.

Multi-attribute decision supporting systems need to handle qualitative and quantitative information, missing data, and uncertainty. A team of experts from the academy and the industry - coordinated by the authors - developed an indicator framework and evaluation process to fit DM and construction decision support but could be applied later in other sectors and regions.

The developed MADSS was used to analyse distributed manufacturing and traditional construction alternatives from economic, social, environmental, and resilience perspectives in New Zealand to demonstrate applicability.
The critical research contributions are:

- further exploring DM impacts across the supply chain (for instance, adding local sourcing and handling reverse logistics),
- proposing a flexible decision supporting process and framework to engage with stakeholders and support decision-makers in other industries and regions,
- and introducing the DM sustainability trade-offs in the construction industry in New Zealand.

Keywords
Distributed Manufacturing, Supply Chain, Multi-attribute decision support, Sustainability, Construction

1. Introduction

Distributed manufacturing (DM) refers to manufacturing goods close to the end-user (Srai et al., 2016). A part of the industries continuously increased centralisation and specialisation to use the economy of scale, like automotive and computer technologies. Other industries held their production close to their end customers due to perishable products (e.g., bakeries) or services they provide (e.g., catering). Also, there are combined solutions to ensure high productivity by centralising production and finalising the show close to the customer. For instance, large baking companies distribute ready-to-bake dough and pre-baked bread in their network (Matt et al., 2015).Distributed manufacturing raises interest in the earlier centralised supply chain, enabling technologies like 3D printing, robots, computerisation, and cloud-based technologies. Distributed Manufacturing (DM) has five essential characteristics: digitalisation, personalisation, new enabling technologies, localisation, and enhanced user and producer participation (Srai et al., 2016). DM provides greater flexibility, responsiveness, and higher supply chain reliability. It benefits the production systems by allowing production anywhere, given the availability of local resources and technologies. It is agile, can operate at a small scale, and face fewer restrictions on where to be located (Srai et al., 2016). Small-scale distributed operations allow the production in places such as hospitals or even disaster areas.

Significance of distributed manufacturing:

1. Identified as one of the ten most promising emerging technology by the World Economic Forum
2. McKinsey 2013 – disruptive technologies
3. Manufacturing has long been important to New Zealand’s economy. In 2007, the manufacturing sector was worth over 14% of the GDP. It has slipped to 12% in the past decade, and discussion on rejuvenating the industry has begun.
4. Consumers are increasingly expecting manufacturers to switch from fossil fuel-based to renewable bio-based resources and adopt circular economy principles where materials are used and reused efficiently.
5. Rapid growth in disruptive manufacturing by 3D printing – no spare parts, robotic manufacture, personal customisation on the spot, e.g., hearing aids, dentistry, sunglasses

A distributed manufacturing supply chain could look like the following futuristic example:

1. Producing cellulose for bioplastic on the farm
2. Ordering a car part online
3. Getting the blueprint from the car manufacturer
4. Printing out the part at the local 3D printing centre (e.g., in a post office) by using locally produced bioplastic

The benefits offered are the lower capital and logistic costs (eliminated waste from transportation), better customisation, faster service, and lower risks of investments since the flexible technology does not depend on a specific product or style that is temporarily demanded.

While some areas were investigated earlier, some other aspects are neglected:

- While challenges of DM is mainly in the operations, most of the benefits are in the connected supply chains,
- Available raw materials close to the end-users. For instance, biomass production for bioplastics and bioplastic raw material used in DM.

DM is only possible when the production and technology are ready. It requires maturity of technology, understanding of material properties, material control, consumer base, supplier base. Infrastructure is crucial for the long-term adoption of DM. Moreover, governance and regulatory issues should be addressed to facilitate the acceptance and spread of DM.

Small and middle-size companies, farmers, communities, and Maori can benefit from the low-cost and highly flexible solutions since they can own a more substantial part of the supply chain and produce higher-value products. Distributed manufacturing can reduce the competition for land (food versus non-food); for instance, farmers could sell high-value processed products like sawn wood even prefabricated house panels instead of getting the stumpage for their trees. The value/ha/year could be 3 to 10 times higher. Therefore, they use less land for achieving the same benefit.

Potential benefits of DM:
- Improving perceived quality and value.
- Regional development opportunities.
- Healthier communities through localised jobs and close to home manufacturing enable local development, and higher value add manufacture cutting commodity approaches to growing GDP.
- Improved environmental performance through reduced infrastructure and more just in time manufacture, with reduced waste and storage needs and promoting the development of Biobased replacements for petroleum/coal-based manufacturing and society.
- Low emissions by reducing transport needs on the roads and at sea through close to end-use manufacture.

1.1 Objectives
The goal is to set up an evaluation framework for DM applications and introduce the evaluation framework on case studies.

Research questions:
- What are the critical factors of the benefits and costs, and what are the barriers to overcome?
- What are the key trade-offs and constraints?
- How could we evaluate the feasibility of a DM supply chain?

2. Methods

2.1 Data collection
The first part was a literature review and a desktop study listing the promising value chains for distributed manufacturing solutions. Then, we used the Delphi method to evaluate those opportunities to create a shortlist of business cases to elaborate on later with the support of Lincoln University experts.

2.2 Data analysis
The multi-Attribute Decision Support System (MADSS) model was used to identify and analyse DM (Efroymson et al., 2013). The Delphi method was applied by supply chain and sustainability experts to identify and evaluate the critical factors and the structure of how they influence the decisions.

2.3 Case Studies
For testing the decision-supporting tool, the experts' panel considered two case study constructions.

1. **Residential building construction following DM principles in an NZ township**
   - Using local materials. Wood source from the forest nearby and processed in a mobile sawmill. Reclaimed materials used from earlier deconstructions.
   - Insulation is from agricultural residues (straw).
   - Foundation is large log columns.
   - Detailed construction plan and instruction provided by a DM expert architect.
   - Local people are employed.

2. **Residential building construction as usual in an NZ township**
   - Using low-cost materials bought from wholesales. The wood source is unknown—logs processed in large or

medium-sized sawmills. No local people are involved in lumber production.
- Insulation is imported, production is from virgin material.
- Concrete foundation.
- Construction is by a developer team of a national company.

3. Results and Discussion

Based on the literature review, the expert panel proposed a list of indicator structures to evaluate Distributed Manufacturing in Construction (Table 1). Beyond the identified indicators, the proposed system guides the weight of the indicators and sub-categories.

Table 1. List of indicators used for this study

Attributes	Sub-category	Indicator
Social sustainability	Social well-being	Number of local people hired
		Household income
	Job security	Probability of keeping jobs
	Worker safety and labour health	Workdays lost due to injury/illness.
	Social acceptability	Public acceptance
Economic sustainability	Costs	Operation costs
		Logistics costs
	Profitability	Return on investment (ROI)
		Variability in annual profit
	Productivity	By employee
		By fossil energy used
		By natural resources
Environmental sustainability	Energy consumption	Energy consumption
		Renewable energy use
	Water quality and quantity	Contaminated water release
		Water use
	Using green technologies	Circular technologies: recycling and waste reduction
		Reducing virgin material consumption
	Air quality	Greenhouse gases
		Local and regional pollution
Resilience	Flexibility	flexibility in production in terms of volume of order and production schedule
		multi-skilled workforce to continue production
		Flexibility in sourcing (local sourcing)
	Responsiveness	Quick response to sudden shifts in market
		Adequate response (response team)
	Collaboration	Regular information sharing with supply chain partners
		Visibility along the supply chain
		Conflict resolution system (risk sharing)
	Learning – Knowledge Management	Training and continuous improvement
		Strong knowledge base

Individual indicators were evaluated and discussed in detail by the panel of experts, and the following scale was applied: 1 Unfavorable; 2 Neutral; 3 Favorable.
The discussion included comparisons, current and future situations, assumptions until experts agreed on the indicator value and the evaluation's limitations.

Evaluation
All indicators were applied and concluded in spider web diagrams. Figure 1. summarises all sustainability attributes included in the evaluation. For the Figures, the closer the edges, the more favourable outcome is, and the closer to the centre, the less good result. In all Sustainability attributes, DM construction was found more profitable than the traditional way of building houses in New Zealand. DM provided the most significant advantages from environmental and sustainability, less from a social perspective, and the least from an economic perspective.

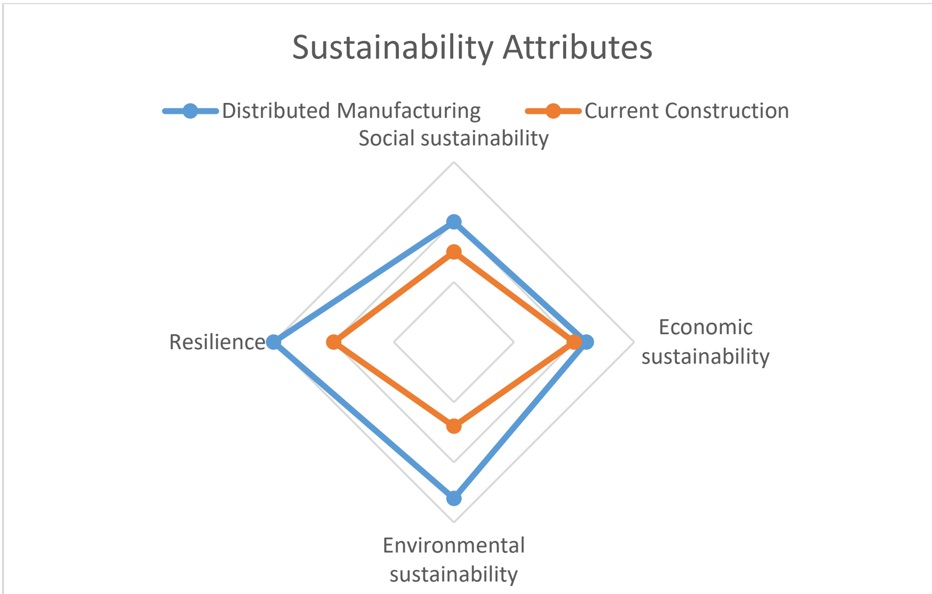

Figure 1 Sustainability Attributes

Social attributes' evaluation is introduced in Figure 2. While DM is advantageous in most of the categories (Social well-being the most), job security was evaluated better in the case of traditional construction.

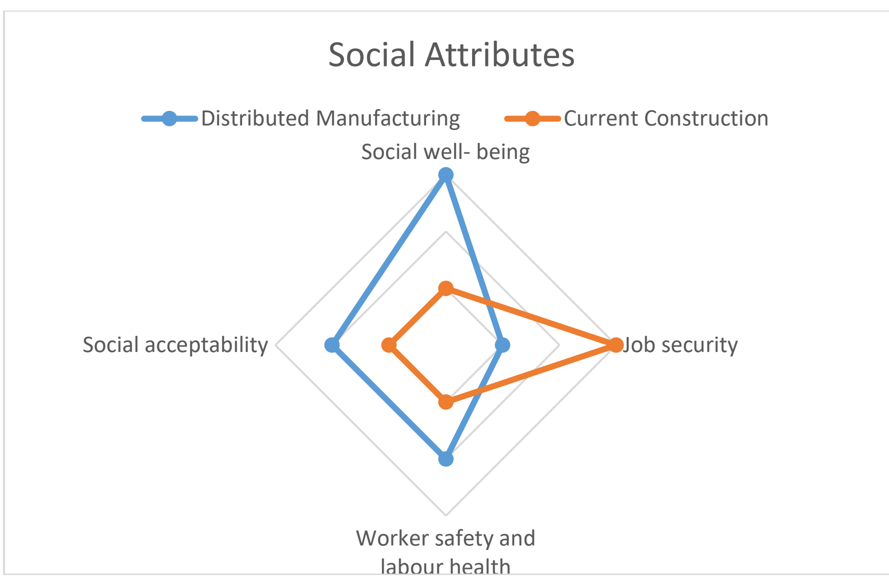

Figure 2 Social Attributes

Economic attributes are in Figure 3. DM performed slightly better from costs and productivity perspective but slightly poorer from a profitability perspective.

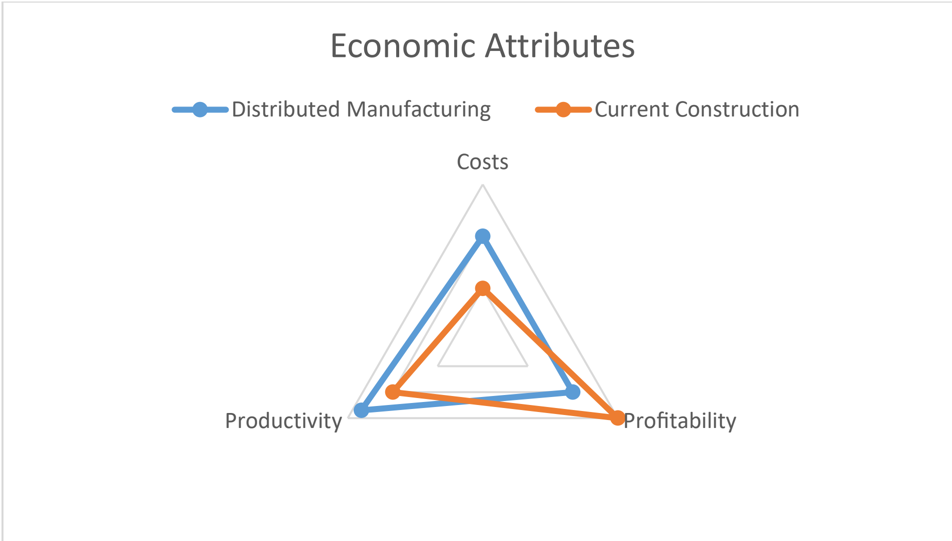

Figure 3 Economic Attributes

Environmental attributes are in Figure 4. DM largely overperformed traditional construction from an ecological viewpoint. From a water quality perspective, the evaluation did not show any difference.

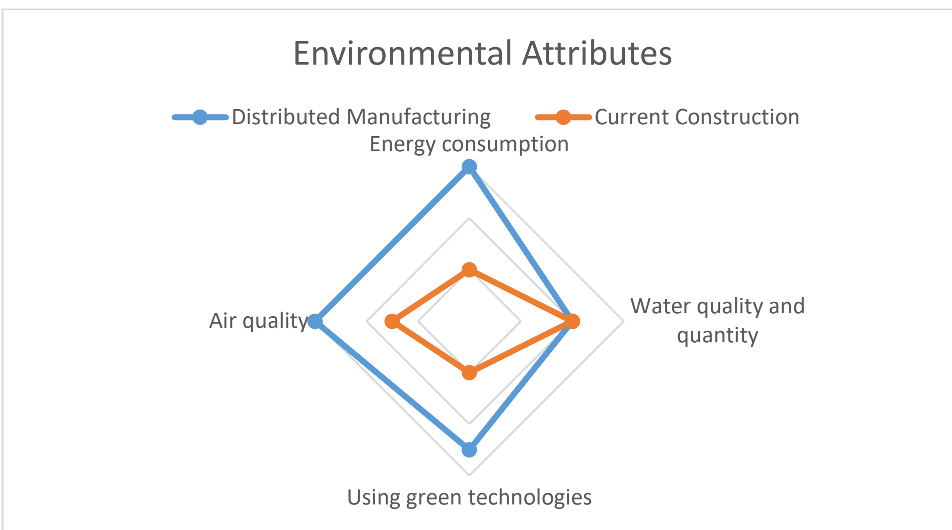

Figure 4 Environmental Attributes

Resilience attributes are in Figure 5. DM was found better than traditional construction from a resilience standpoint in all categories except knowledge management. While the diversity of available knowledge increases by applying DM principles, traditional construction's well-organized, centralised training methods also provide advantages.

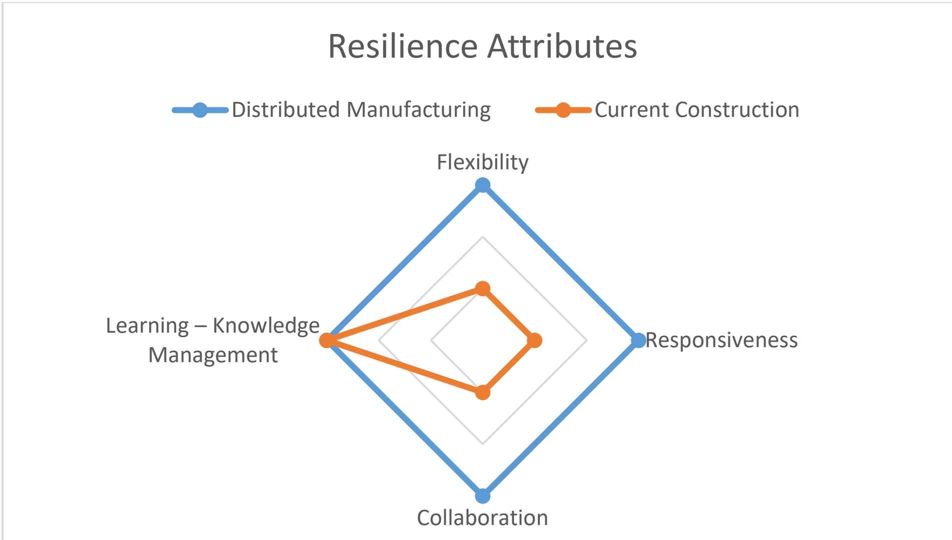

Figure 5. Resilience Attributes

5. Conclusion

While DM has practised for centuries, automatisation, globalisation, new technologies, and the need for resilient and sustainable supply chains provide new opportunities. At an early stage, applying a Multi-Attribute Decision Supporting System is helpful to explore the feasibility and discuss the operation model with stakeholders. We found that the key advantages are:

- Can be used in case of incomplete or lack of quantitative data
- Based on experts' opinions, group decision
- Support stakeholders' discussions
- Decisions based on predefined decision functions

The analysed construction case studies indicate that DM is advantageous from sustainability. However, the profitability of the DM supply chain need to be further developed and uncertainty further reduced.

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Bibliographies

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Muhammad Umar, PhD, is currently a Lecturer of Supply Chain Management at the agribusiness and commerce department, Lincoln University. He holds an undergraduate degree in computer and information sciences, a Master's in project management and a Ph. D in supply chain management. He has worked in the industry for several years before joining academia in 2012. His primary research interest is developing optimal approaches to design resilient and sustainable supply chains where quality, costs, lead time, flexibility, reliability, logistics and risks are effectively managed. Supply chain management (SCM) is an integral part of most businesses and is essential to organisational success. Nevertheless, SCM boosts customer services and reduces operating costs. Still, SCM also helps sustain human life by delivering food and water to masses; it improves human healthcare and protects humans from climate extremes. Recently, his research has introduced a supply chain resilience framework that has brought together four crucial supply chain management areas: collaboration, knowledge management, logistics and sourcing. Further, one of his papers is recently published in the Journal of Knowledge Management that has contributed to linking the knowledge management areas to achieve supply chain resilience. He has also recently completed one project where his team has introduced Haddon Matrix to report evidence-based supply chain resilience strategies against covid19 related disruptions. Currently, he is working on resilience and optimisation of food, export, forestry-related supply chains in New Zealand.

Linh NK Duong, PhD, current research interests focus on sustainable and resilient supply chain management linked to digital transformation, innovation, and collaboration among supply chain partners. He focuses on vulnerable contexts such as the agri-food industry, tourism industry, or small and medium enterprises (SMEs). His papers relating to supply chain resiliency and sustainable innovation were published in the International Journal of Production Research, Journal of Macromaketing, and Trends in Food Science and Technology.