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Impact of strategic control and supply chain management on recycled plastic additive manufacturing

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ABSTRACT

Climate change due to greenhouse gas emissions is the most important issue in the world, threatening our lives. Studies reveal that most emissions are caused by transportation (29%), manufacturing (23%), and irregular population distribution across the world. This study suggests the localization of recycling and manufacturing plastic parts and components by additive manufacturing. Localization will decrease transportation, resulting in reduced energy consumption and CO_2 emissions. However, the method may not be sufficient because local additive manufacturing means less reliance on supply chains and higher dependence on the workforce in rural areas. Factors such as the workforce in rural areas, multientity authorities, and policy are important to the realization of sustainable manufacturing. In this study, a novel strategic control model is proposed to focus on human-centric approaches. The strategic control model proposes methods to connect strategic planning with demography and the workforce and to apply control metrics to relocate overcrowded populations to rural areas. The strategic control model realizes localization through workforce allocation and home-based manufacturing. It streamlines the integration between recycling, manufacturing, and distribution. As a result, decreased reliance on the supply chain reduces transportation, energy consumption, CO_2 emissions, and cost. It also creates job opportunities and mitigates societal issues.

1. Introduction

Our previous work compares additive manufacturing (AM) and conventional manufacturing (CM) in terms of energy consumption, transportation, CO_2 emissions, material yields, and the cost in a full life cycle assessment (LCA). Benchmarking between recycled materials and primary materials is also conducted through experiments supported by Monte Carlo simulation, the divide-and-conquer algorithm, and data analysis. The results reveal that through a robust integration of AM process, materials recycling, and localization, the combined approach positions AM in a better standpoint of sustainable manufacturing in the plastics industry. Integration of AM process means a better control between collection, plastics recycling and manufacturing (Wu, 2021a).

Transportation in automotive industry can cause significant impacts to environment, and localization in manufacturing industry can eliminate such issues and achieve a better sustainability (Mayyas et al., 2012). Transportation distance can be minimized in an integrated AM process. Elimination of inefficient transportation of plastics waste can improve recycling efficiency, and reduce energy consumption and CO_2 emission (Ortúzar, 2021). Consequently, environmental sustainability can be achieved through local recycling and manufacturing.

Localization minimizes insourcing process in source materials transportation (Mourdoukoutas, 2015), as localization simplify supply chains, and minimize transportation of waste materials (Garmulewicz et al., 2016). Among the combined approach, the localization has been a tactical factor and crucial to sustainable manufacturing because localization reduces reliance on supply chains, transportation, and CO_2 emissions.

Realization of localization cannot be achieved in one step as it requires strategy and control to rationalize the demography, and facilitate tremendous workforce to support AM in rural areas. Through the gap analysis, none of the existing literature adheres to human capital areas, such as workforce, policy, population, and regulations, to support AM localization and the elimination of supply chain logistics. For this reason, AM's advantages cannot be fully utilized due to the missing of human capital factors.

It is crucial to AM to prevent rural-to-urban abnormal migration and allocates a robust workforce in supporting the localization of AM in rural

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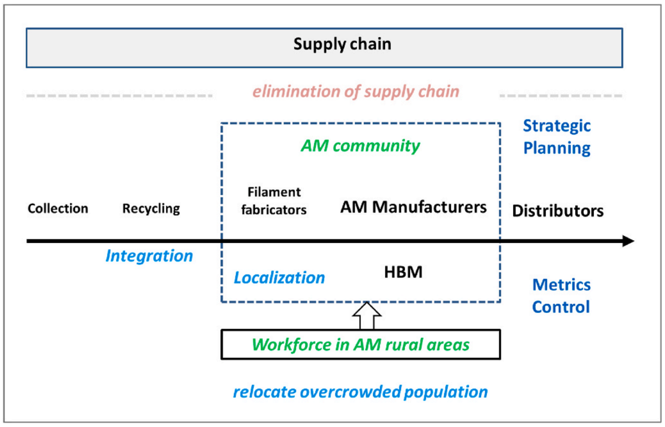

Fig. 1. Local manufacturing, integrated AM processes, and AM community.

areas (Jones, F., et al., 2021). To achieve the goals, the strategic control model is proposed to as a win-win approach supporting sustainable manufacturing. The model applies strategic planning in a metric control of population and infrastructure, and it creates job opportunities in rural or suburban areas. The novelty of this study narrows down AM's focus to the local supply of the workforce in terms of sustainable recycling, manufacturing, and distribution. The model shifts the focus of AM's demands to local supply in terms of workforce, technologies, materials, and applications.

In a seamless integration and AM process, home-based manufacturing (HBM) is a critical part of AM localization enabling the seamless integration (Inimake, 2021). A previous study indicates that CM usually utilizes a centralized manufacturer or a final plant to assemble the parts fabricated by multiplants that cannot be easily changed. Multiplant dependencies increase risks, transportation, CO_2 emissions, and costs (Khajavi et al., 2013), which also slows down design and production lead times. By contrast, AM can print the products or parts in fewer steps or in one single step, diminishing the reliance on supply chains and logistics, and reducing transportation and CO_2 emissions. However, localization cannot be realized in a single step. It requires a few steps to achieve this goal.

Because localization requires massive labour to work in AM communities, the relocation of the workforce from overcrowded areas to AM communities is crucial to support localization in rural areas. The strategic control model is expected to avoid the abnormal movement of labour from rural to urban contexts, satisfying time demands and mitigating problems. As indicated in Fig. 1, the allocation of a massive workforce in the AM community, including HBM, enables more robust integration (Shanmugam and Das, 2020), eliminating supply chain and logistics engagement and solving the speed and scale production problems. The model is also expected to attract workers by offering job opportunities and supporting the same quality of life in the rural AM community as is enjoyed in urban areas (Kjaerheim, 2005), helping achieve a more sustainable society.

2. Literature review

The existing literature has been reviewed in the related sub-areas of sustainability: localization, transportation, CO_2 emissions, supply chain, decentralization, and workforce. Among these, the workforce, as a key factor of this study, is reviewed for its linkages to other factors in the realization of sustainable manufacturing.

It is highly recognized that the localization of AM using recycled plastics can contribute to environmental protection by reducing energy consumption and CO_2 emissions due to less transportation. However, the existing literature has failed to compare and conclude the energy consumption and environmental impacts. The literature indicates that it may not be easy for AM to simultaneously fulfil the diverse requirements of different parts by using uniform process parameters (Peng et al., 2020). These uncertainties have slowed down AM's growth. A recent study has further considered the hydraulic valve as the key source for the high electricity demand of the AM process and environmental degradation (Zhu and al, 2021). However, this viewpoint may not reflect reality. In an enhancement of gradient processing, the multisetting of process parameters is used to handle the associated parts of the valve body. The results reveal that gradient processing can reduce the coefficients of friction by 50%, and the lightweight design of AM contributes 20% savings to energy consumption (Alamgir et al., 2018).

Table 1
Comparison of CO_2 emissions in transportation and manufacturing data source (Wu, 2021a):

method vs. factors	Recycled plastics		Primary plastic	
Manufacturing (t of CO_2 emission/t of plastic)	AM	0.75	AM	2.4
	CM	(averaged)	CM	(averaged)
Transportation (t of CO_2 emission/t of plastic)	AM	55 (estimated)		
	CM	1375 (estimated)		

In addition, an energy assessment in the LCA reveals that compared to energy consumption in transportation, the energy consumption in the manufacturing process shall not be the cause that threatens the environment. Previous research (Wu, 2021a) indicates that CO_2 emissions due to transportation are 0.11 t of CO_2 per t-km of plastic materials. However, the CO_2 emissions (t CO_2/t plastic) in manufacturing process only range from 0.5 to 1.0 for recycled materials. In general, a minimum of 500 km of local transportation by truck is standard in AM, which produces 55 t of CO_2 per t of plastic. For CM, because extensive logistics are involved, CO_2 emissions are estimated at 25 times that of the CO_2 emissions of AM, meaning that 1,375t of CO_2 can be produced in the transportation of CM. Comparatively, the CO_2 emissions caused by transportation are over 20 times that of the CO_2 emissions in the manufacturing process, as indicated in Table 1.

Localization reduces transportation distance. The novelty of the strategic control model is not limited to the priority setting. More important, it sheds light on the importance of transportation, and it applies the advantages of AM's natural characteristics to reduce reliance on the supply chain (Garmulewicz et al., 2016).

The simplification of the processes benefits producers and consumers. Attaran (2020) indicated five ways AM is breaking through current supply chain models: mass customization, disruptive competitors, decentralized manufacturing, on-demand manufacturing, and sustainability. Among these, on-demand manufacturing and low-cost mass customization are the key factors enabling speedy product design and efficient delivery. Waste is reduced due to the possibility of creating parts on demand (Ribeiro et al., 2020). The reliance on supply chains is diminished because most of the parts and assembly can be completed by one plant. Additionally, heavy components can be substituted with lightweight ones. The concept of waste reduction is critical to cost savings. However, these factors in cost reduction are seldom reflected in the existing literature.

Additive manufacturing of recycled plastics has been a preferred method in supply chain elimination, and decentralized AM can significantly reduce lead time, cost, and risk. Localization is predicted to become the future trend, and long supply chains will shrink (Khajavi et al., 2013).

Decentralization supports localization because parts fabrication does not rely on a centralized hub. However, AM can face some legal and regulatory challenges because the products may not be easily traced to their origin, which has implications for liability in the case of damage (Ben-Ner and Siemsen, 2017). In a modernized information world, traceability, legality, and liability are resolvable in a transparent cloud environment.

In general, decentralization is more suitable for higher-volume

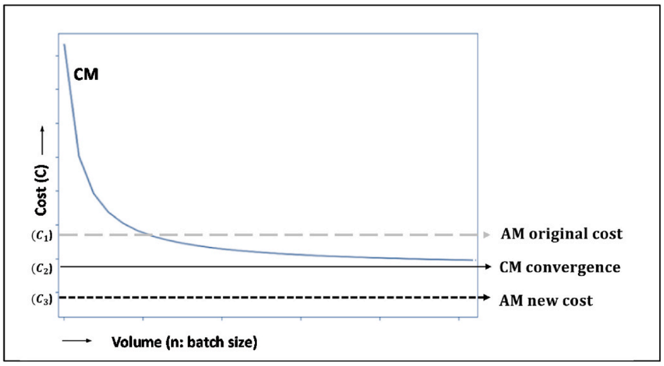

Fig. 2. Cost evaluation for different conditions (Wu, 2021b).

products of local distribution. For various small-scale products, scale, part size, materials limitation, mechanical properties, surface quality, and accuracy can be challenges that rely on a concrete foundation of AM standards (Abdulhameed et al., 2019).

Increasing the scale and speed of AM production can improve the disadvantages caused by decentralization. AM prints products at a lower speed and is limited to producing premium quality, smaller quantity, and smaller size products (Lee et al., 2017). AM has the potential to fully utilize the collaborative pattern in a full-scale provision. The pattern is expected to support cost estimation and to offer an opportunity for HBMs to solve the scale and speed issues. In addition, some companies are developing new 3D printers equipped with thousands of diode lasers, which could significantly accelerate printing time (AMFG, 2020).

In addition to scaling production, AM has some barriers to overcome before becoming the industry standard. There is no concrete cost model for the life cycle analysis of AM in the literature to quantify its individual unit costs. This has created concerns and barriers to estimating the cost of AM for comparison. Wu (2021b) indicated that the cost of AM is volume independent, whereas a lower cost per part can be achieved for high volumes in CM. This constraint limits CM from service on demand and leaves ambiguity in the threshold setting of a critical batch volume. A comparison is indicated in Fig. 2.

From the perspective of societal impact, AM applications in crisis handling and medical care are unique advantages of AM, and distributed plastic recycling for open-source programs is a typical example of plastic AM applications in this area (Santander et al., 2020). In addition, because AM has the potential to reduce complexity and reliance on supply chains, AM supports humanitarian organizations in emergencies by enabling local production and maximizing the benefit in humanitarian purposes (Corsini et al., 2020).

It is important for a multientity to have transparent communications, and human-centric factors cannot be avoided. Within the decisive factors, a close linkage between local supply and AM workforce is crucial in terms of demographical planning, AM workforce strategy, and migration flow control.

Urbanization has been necessary to support the economics of the nation; however, rapid population growth in urban areas has affected local AM manufacturing and supply (Ray, 2011), indicating that abnormal population growth threatens the environment and causes labour shortage for AM in rural or suburban areas.

In addition, an urban-centric approach does not favour pandemic crisis handling and can damage a harmonic society. For instance, vagrant people in large cities contribute to the virus's spread, and social distance becomes a significant issue due to the shortage of accommodation. These factors threaten a healthy society and cause significant impacts on quality of life.

Lack of strategic planning in the sustainable manufacturing of the plastic industry has been a gap that can be harmful. The existing literature has viewed rural-to-urban migration as a shortcut for economies rather than considering how this shortcut affects the environment and society (Gebrea and Gebremedhinb, 2019).

For this reason, the UN Human Settlements Program has advised that migration flow requires critical review. Ad hoc labour sourcing may satisfy timely demands, but it leaves behind problems (UN-Habitat, 2017). It has ruined rural development, damaged economies, broken ecological balance, and increased crime.

Overpopulation has been a major issue degrading sustainability levels. Moving the overcrowded population now in urban areas into rural areas could provide a powerful workforce to support AM because relocating the overcrowded population to rural areas promotes rural development and job opportunities towards sustainability. Local manufacturing via AM is becoming a trend due to technological advancements (Kleera and Pillerb, 2019). Under well-planned AM demography and workforce control, supply chains and logistics can be significantly reduced or even avoided (Akbari and Ha, 2020).

Table 2
Evaluation of AM and CM from a sustainability point of view.

Method	Trans. & Log.	Supply chain	Local.	CO_2	Lead time	Prot.	Energy		Standard	M. yield	Mass prod.	Job opp.	Rural dev.	SC applic.
							T	M						
AM	+	+	+	+	+	+	+	N/A		N/A		+	+	+
CM									+		+			

Denotation (cells in cyan are areas needing improvement)

'+'	Advantage	
N/A	Conclusive result is not available	
Notation	Full word	Description
Trans. & Log.	Transportation and logistics	Distance and method of transportation
Supply chain	Supply chain	Complexity, cost, time, and risk measurement
Local.	Localization	Collection, recycling, and manufacturing take place locally
CO_2	CO_2 emission	Two major sources of CO_2: manufacturing and transportation
Lead time	Lead Time	Time required from quotation to delivery
Prot.	Prototyping	Sample of design before production
Energy	Energy consumption (T: Transportation)	AM is a better option because transportation can be minimized
	Energy consumption (M: Manufacturing)	No indicator shows that AM can be a better option
Standard	Standardization	Standards used by global organization and commonly recognized
M. yield	Materials yields	No indicator shows that AM can be a better option
Mass prod.	Mass production	High scale of production; lead time is independent of batch volume
Job opp.	Job opportunity	Job opportunities for skilled labour with training program provided
Rural dev.	Rural development	Development in rural or suburban areas
SC applic.	Strategic control applicability	Feasibility study for whether strategic control is applicable

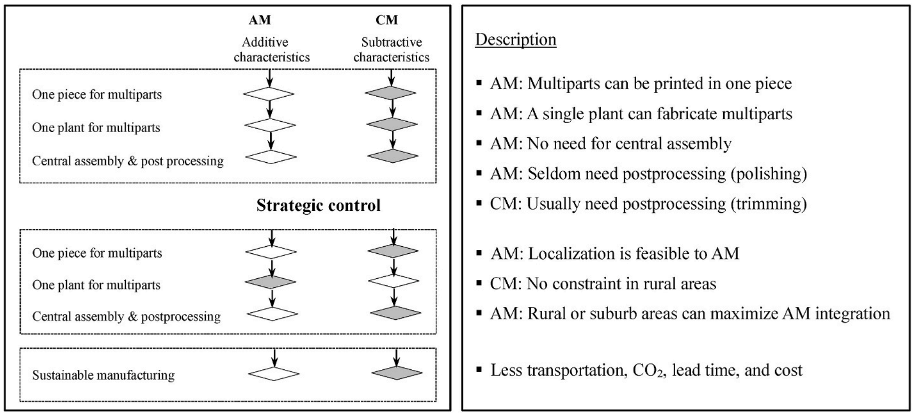

Fig. 3. Sequence and flowchart of factors enablement of AM and CM.

3. Methodology

Sustainability is composed of three key aspects: economies, environment, and society, and each of which correlate with one another (Strange and Bayley, 2008). Through the literature review, it can be seen that the AM of recycled plastics has great potential to replace CM processes for some applications as AM can effectively achieve sustainability from all of these aspects. AM is important to sustainable manufacturing particularly in reducing energy consumption and CO_2 emissions, saving cost and supporting a healthy society. However, the existing literature has addressed fragmented aspect rather than an optimized method covering the whole. In addition, the literature is lacking control metrics and is misleading regarding the priority of AM development. For instance, gap analysis of the literature review leads to an assumption that the transportation can be the major contributor of CO_2 emissions, threating the environment (Wu, 2021a). Strategic control effectively addresses the gap, and proposes method to strengthen the foundation of AM advantages, realize a substantial reduction in transportation, and maximize AM's natural advantages.

Gap analysis further reveals that sustainable manufacturing relies on a human-centric model to rigorously assess technologies, processes, and applications. Decreased reliance on supply chains in AM means a higher dependency on the local workforce. Without strategic control, overcrowded populations can abuse labour efforts and energy consumption, which affects sustainability in terms of the workforce and resources.

The novel strategic control model can eliminate transportation and reliance on the supply chain through realizing the seamless integration of local manufacturing and local recycling. For this reason, energy consumption, CO_2 emissions, warehousing, lead time, and cost can be significantly reduced, and the robust integration of plastic manufacturing can be established through the AM community, including HBM. However, the realization of seamless integration cannot be reached with only one stroke. The scope fully covers various human factors, such as relocating the overcrowded population to rural areas, rural development, job opportunities, and a robust workforce, including HBM, to support the localization of AM towards sustainability.

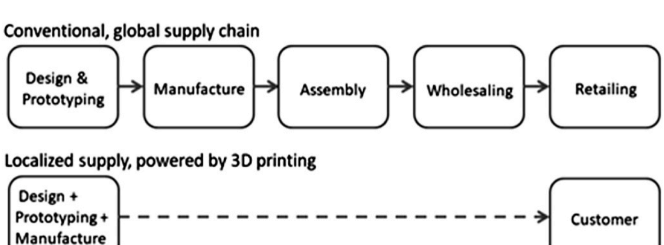

Fig. 4. Comparison between conventional supply chains and the new one.

To demonstrate the current status and the gap, Table 2 illustrates and compares AM and CM based on previous studies (Wu, 2021a). In this table, the colour cyan stands for the factors that need improvement from AM. There are three types of factors, and the methods applied for each can differ.

Type1: The factors in white are AM characteristics and do not need extensive development work.

Type 2: The factors in cyan without the '+' sign are not AM's advantages. Both standard and scaling production are disadvantages of AM that requiring more development to enhance capability.

Type 3: The factors in cyan with the '+' sign are AM's advantages. They cover the strategic control applicability, rural development, and job opportunities in rural areas. This category plays two roles. First, it is expected to strengthen the foundation of type 1 and achieve sustainable development. Second, it supports the enablement of type 2, and it allocates sufficient workforce and control metrics to achieve mass production based on demand.

To better illustrate the sequence in terms of tactical factors and consequent factors, Fig. 3 applies a flowchart to demonstrate the interoperability and relations between factors. The first block covers the natural characteristics of AM and CM, and these are the reasons that localization and reduced reliance on the supply chain are feasible in AM. The second block is the tool to enable and realize AM's advantages in the first block. The third block is the consequence of blocks one and two. The white colour in each decision point stands indicates it is 'positive' or feasible, and the grey colour means it is infeasible or that a constraint is applied. For example, rural workforce dependencies can be seen in AM but not in CM because localization is not an advantage to CM.

3.1. Local manufacturing methods and applications

The objective of local manufacturing is to apply the integrated local manufacturing of the AM community to reduce the reliance on supply chains. This implies the materials flow or product flow will be transformed into logical collaborations. From a supply chain perspective, AM is known to be an effective way to promote structural changes in (1) reducing inventory and assembling and disassembling cost and efforts; (2) enabling on-demand spare parts with no stock, customization, and personalization; (3) reducing gaps to consumers; and (4) reducing the labour effort through decentralized production.

Through the fact of less reliance on supply chains, AM is paving the way towards enhanced humanitarianism. The humanitarian supply chain is a particular supply chain that usually takes place when a community faces unprecedented urgency, such as during natural disasters or pandemic crises. It differs from commercial supply chains in its temporal time frame, unpredictability, and resource constraints. During the COVID-19 pandemic, AM played a significant role in assisting the medical supply chain in urgent cases (Belhouideg, 2020). Rapid

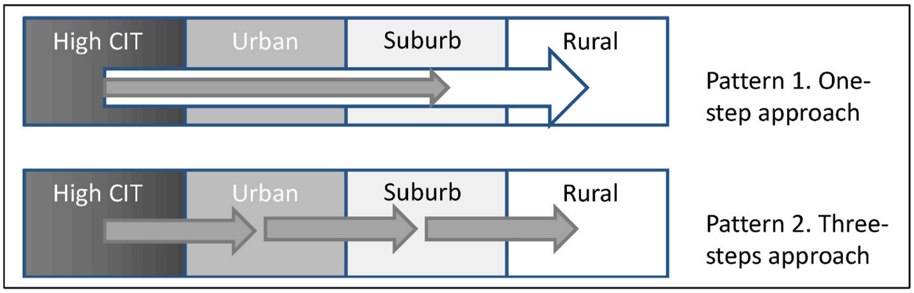

Fig. 5. Patterns benchmarking of demographical rationalization in strategic planning.

prototyping enabled the design of medical devices, such as face masks, ventilators, and testing swabs, to be instantly materialized, and it provided tremendous value because components could be made on-demand locally instead of pending overseas production. These not only save time and cost but also reduce pollution and CO_2 emissions through the elimination of supply chains and logistics.

The nature of AM shortens the distance in design, manufacturing, and marketing, which could transform the global supply chain into a globally connected but locally supplied chain. With local sourcing, AM has the potential to revolutionize established supply chains into efficient, sustainable local systems. Fig. 4 illustrates the transformation from global to local supply chains. The global supply chains will turn into local ones, factories will become larger, ships and malls will become smaller, and long supply chains will shrink. Many jobs will combine design, production, and sales into one.

With the diminishing of supply chains due to the quick growth of AM, socially oriented firms hope to adapt to the transformation, but they lack the means to change when entering new markets due to insufficient experience among stakeholders in making such changes. The digital nature of AM also creates opportunities for customers to contribute through open design, making it possible for small firms and individuals to share resources and innovate more efficiently. In this way, AM allows producers to engage closely with customers, including customized products, and the firms can take care of producers.

3.2. Strategic control method

The main objective of the strategic control model is to prevent abnormal migration from rural to urban areas and to relocate the overcrowded population to rural or suburban areas to support the AM community and businesses. To make the framework concrete, the human factors of top-down approaches are inevitable, and engagement from multientities cannot be avoided.

There are many dependencies that rely on human-centric investigations, including demographic planning, policy, regulations, and the workforce. For this reason, the strategic control model is proposed to investigate and supplement human factors in sustainable manufacturing for rural development. Raw data from 200 nations are consolidated, aggregated, and analysed.

As indicated in the previous subsections, because AM does not require an assembly or tooling process, the dependency of AM on supply chains and logistics can be minimized. The advantages of AM in localization and local supply and the reliance on a labour force from overpopulated urban areas can be combined into a robust workforce to support AM businesses in rural development, which can be integrated into a hub-like network to realize sustainable manufacturing. Among these, our priorities are to prevent abnormal migration from rural to urban areas and to relocate overcrowded populations to rural or suburban areas to join the AM community and to support AM businesses. The method, measurement, and approaches are elaborated as follows.

3.2.1. Measurement methods of control metrics

In this top-down approach, the strategic control model applies the key indicators to guide population balancing, and the key indicators are as follows: the crowdedness index of the top 300 cities (CIT) and the rural population ratio (RPR).

The CIT is a measurement of the crowdedness of a nation. For instance, the CIT for any particular nation is the sum of the population of all cities in the top 300 list divided by the sum of the land area of the listed cities. An overcrowded CIT can be an indicator of abnormal sustainability, which affects AM development.

The RPR is the sum of the population in rural areas divided by the total population of a nation. For instance, if the sum of a nation's population is 100 million, and the sum of the population of all its rural areas is 25 million, then the RPR of that nation will be 25%. There is a guideline, but the optimized RPR for each nation varies.

3.2.2. Measurement method for sustainable environment, economics and society

The Environmental Performance Index **(**EPI**)** provides a data-driven summary of the state of sustainability around the world by using 32 performance indicators across 11 issue categories. The EPI score is used to evaluate the impacts of the CIT and RPR on the sustainable environment of a nation, and it ranks 180 countries on environmental health and ecosystem vitality. Gross domestic product per capita (GDPpc) is the average of individual incomes. A GDPpc of <$10,000/year is the lower range. The GDP growth rate (GDPgr) is the average yearly growth rate of GDPpc compared to the previous year. Both metrics are used to evaluate the impacts of the CIT and RPR on sustainable economies. Rationalization of demography not only supports AM local workforce, it eliminates society issues and pandemic crises caused by the vagrants. For this reason, CIT and RPR are used, as control metrics, to evaluate the sustainable societies.

3.2.3. Infrastructure strategic planning for control metrics

The approaches of the strategic control model refer to the top-down governance of demography, job allocation, and infrastructure planning, so various industrialization plans can be implemented in rural or suburban areas. Instead of enforcement, the strategic control model encourages and attracts workers by offering AM job opportunities and establishing livelihoods of equal quality in suburban or rural areas. As a case study, the rural development program in the United States has applied AM to fabricate equipment and develop job opportunities in rural areas (Legg, 2021). For the time being, the Career and Technical Education programs in the United States have developed new advanced manufacturing training to develop rural areas and maintain competency in urban areas while preventing rural-to-urban migration (Jones et al., 2021).

In terms of strategic planning in demographical rationalization, the European Commission (Dijkstra, 2020) classified the degree of urbanisation into three major groups: urban, suburban, and rural. The terminologies being used in rural demography theory are defined as follows:

Urban: A land area with a population of >50,000 and a density of

>1500 inhabitants/km^2 is considered urban.

Suburban: A land area with a population >5000 and a density of >300 inhabitants/km^2 is considered suburban.

Rural: Any land area with a density of <300 inhabitants/km^2 is considered a rural area.

In this study, two patterns are illustrated in Fig. 5, to investigate the effective method in dealing with overcrowding issues.

Pattern 1: Move the overcrowded population that exceeds threshold, directly to rural or suburban areas.

Pattern 2: Takes few steps to move overcrowded population to the next level, until it reaches rural areas.

Among these two patterns, pattern 1 can be the suggested option of demography rationalization. The reasons are: in pattern 2, the areas of urban and suburb shall not be the top priorities in the movement while it can take more effort and time. In addition, it may not effectively implement the strategic planning as the complexity can be high and need more people to be involved. Instead, pattern 1 can be a better option that effectively implements the strategic planning into control metrics to effectively rationalize demography, and produce workforce for AM.

Job opportunity has been a powerful driving force of immigration from rural to urban. With the degrade of living quality in big cities, and increase of unemployment, if the labour market can offer careers in rural areas with same living quality, then the same driving force can move people in the reverse direction.

Over all, job opportunities can be a tactical factor and an effective driving force. Due to the cost saving in transportation, lead time, and materials yield, AM manufacturing has potential to achieve 30.2% yearly growth, and reach $21.5 billion by 2025 (Frost & Sullivan's Global Research, 2016). High yearly growth means job opportunities, and this will create millions of job opportunities in rural areas, and to move the plan for relocation into reality.

3.2.4. Planning

Initially, government and authorities create job opportunities and build infrastructure in accordance with the topology of hub-like industrial centres. This facilitates new inhabitants' livelihoods at hub surroundings and the collaboration between HBM and SME. Recycling and AM plants are planned and aligned with appropriate workforces based on the guidelines of recycling and manufacturing topology.

Infrastructure describes all the facilities that are sufficient to provide inhabitants' livelihoods to develop sustainability in the place of their settlement. In principle, this research proposes the same quality and equal opportunity of accessibility to public infrastructure for both rural and urban areas. To establish a concrete foundation of local manufacturing and supply, this research proposes hub-like centres in the surrounding recycling facilities, and it proposes the construction of manufacturing plants close to these centres to guide SME and HBM practitioners to establish AM businesses.

The realization of the strategic control model will protect environment ecology, enable circular economies, and reduce societal outbreaks caused by homelessness; eventually, the model can effectively achieve a win-win scenario. As well, it enables collaboration across multientities and eases AM's burden, shifting AM's focus to the standardization of technologies, processes, and applications. Through AM, HBM can be the primary workforce for local manufacturing, which fully supports rural and suburban development (Inimake, 2021). New residents of AM communities can easily set up HBM because only hundreds of US dollars are required to establish their AM business.

4. Discussion

The methodology outlines approaches for those areas that need improvement. The literature review and methodology indicate that strategic control can strengthen AM advantages; allocating sufficient workforce can achieve mass production based on demand. Local manufacturing supports AM through demography control to eliminate supply chains and allocate overcrowded population in the AM in rural areas (Arora et al., 2021).

As indicated in the literature review, traceability, decentralization, quality, scale, and speed issues are challenges in AM that need discussion. 1) An AM community and a sharable platform can support traceability in a decentralized system. In a transparent environment, decentralization can be the first step of localization that does not affect traceability, legality, or liability because all transactions are recorded in a common platform in a cloud environment. 2) The deterioration of product properties is due to chain scission reactions caused by the presence of water and trace acidic impurities. To maintain the polymer average molecular weight during recycling, this study proposes a method to avoid the development of moisture in the process, such as through drying and vacuuming and the use of chain extender compounds to prevent chain scission reactions (Messmer, 2019). 3) To solve the speed issue, some companies are developing new 3D printers equipped with thousands of diode lasers that could significantly accelerate printing time (AMFG, 2020). Meanwhile, an AM society, supported by AM multientities and HBM, can resolve scale and speed issues based on local manufacturing on demand.

4.1. Approaches through the proposed methods

The critical missions of the strategic control model include the following.

1) Realize the sufficient workforce in a collaborative model and the approaches across multientities to form AM in society and to establish collaboration.
2) Strengthen the foundation of AM's advantages and reduce transportation. For instance, tasks include determining population numbers and the motivation for reverse migration from urban to rural areas to satisfy the requirements of localization.

AM has a great potential to achieve sustainable manufacturing; however, localization towards sustainability covers the environment, economy, and society, and all three aspects correlate with one another. The existing literature has addressed particular aspects of the impacts rather than an optimization for the whole. A lack of strategy in localization and workforce through population control is the other defect. In addition, missing human-centric factors and control metrics result in a huge gap between theory and practice. To address these issues, the strategic control model is proposed, and the approaches are elaborated.

Much of the literature reveals that AM has potential advantages, including lower cost because of materials saving and better materials yield; however, these advantages do not reflect the reality. The primary reasons that AM saves cost, including transportation reduction and on-demand manufacturing, is because the components from multiple parts can be consolidated in fewer steps. Meanwhile, manufacturing on demand can significantly save cost because the nature of AM characteristics reduces waste. Cost reduction, simple entry for new AM practitioners, and low-cost customization are also key factors that enable speedy product design and efficient delivery. These factors benefit stakeholders, consumers, producers, and environmental sustainability because they reduce cost for easy market entry and environmental sustainability. AM's cost savings enables investment and initial funding to relocate overcrowded population to rural areas. Relocation of the workforce is crucial to supporting AM localization in rural or suburban areas, and the strategic control model prevents abnormal movement, and through AM, HBM can facilitate an enormous workforce.

4.2. Green supply chains

Plastics manufacturers need to develop environmental collaboration with their suppliers to achieve sustainability (AiChin et al., 2015), and

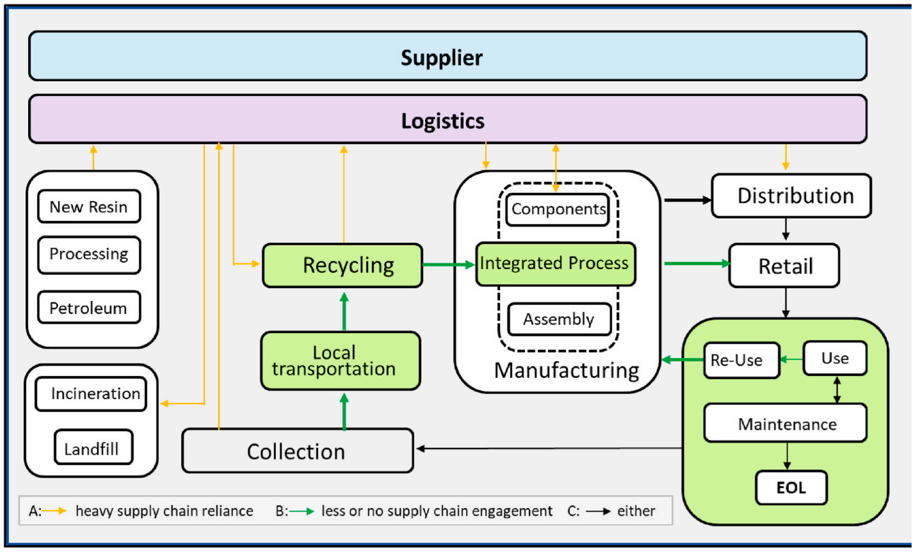

Fig. 6. Regular processes of supply chain and AM closed-loop process.

reduced reliance on supply chains and logistics significantly contributes to sustainable manufacturing. Supply chain management considers suppliers, manufacturers, distributors, warehouses, and retailers to deliver products or services from source to destination. In the supply chain system paradigm, logistics means the transportation of flows in the form of raw materials, products, or services from one place to another place. Supply chain and logistics are based on supply and demand and require many steps, from raw materials to components to semiproducts, end products, and finally the delivery of products to retailers and consumers.

In a supply chain and logistics system, the plant of assembly is the centre that divides the processes into upstream and downstream. The upstream processes mainly cover materials flow, components, or semi-products, whereas the downstream processes take care of inventory, logistics, distribution, and retailing. Upstream mainly cover the flow from materials to end products. The plant of assembly is the boundary between upstream and downstream, and any flow before reaching the assembly plant is upstream activity, such as primary plastics, recycled materials, components, or subsystems. Downstream mainly cover the distribution of end products to consumers. It starts with the assembly plant and includes inventory, logistics distribution, and retailing. To meet the lead time, supply chain management and logistics precisely calculate the time duration of each step.

Due to the requirements of environment protection, the green supply chain has been a significant area of growth in this decade (Mohtashami et al., 2020); however, reducing transportation by eliminating the supply chain can be as much a priority as creating a sustainable environment. In a closed-loop process, a minimum engagement of logistics can double the advantages of transportation reduction and cost savings if reverse logistics are considered (Nikolaoua et al., 2013). To demonstrate this concept, Fig. 6 demonstrates the processes of the supply chain and logistics, including a closed-loop materials flow surrounded by green zones and connected by green lines on which AM focuses.

Distributed manufacturing is the early stage of the green supply chain, which implies that dependencies among suppliers, manufacturers, and consumers are eliminated in both time and space. Eventually, products can be manufactured through a distributed system based on demand and with minimum engagement of supply chains and logistics, so manufacturing can take place in more locations closer to consumers.

In conventional manufacturing, some components may need to be manufactured by different manufacturers of different suppliers while one manufacturer produces the end product, which is isolated in one place. Once the end products are finished, the products need to be distributed through long-distance networks to huge numbers of retailers connected to the large number of consumers. The transformation from CM to distributed AM to local AM is demonstrated in Fig. 7. In distributed production, logistics and warehouses can be significantly reduced because the products can be manufactured at the targeted time and location based on their distance to retailers and consumers. Additionally, combined with retailing, the retailers can shorten the distance between distributed manufacturing and consumers. Eventually, HBM only needs the feed materials in the whole manufacturing process, and the nearby retailers can sell their products without supply chains and logistics.

Furthermore, stock and warehouses are the important elements of the supply chain. The parcel delivery company UPS has adopted AM technologies to optimize logistics flows. The leading supply chain company possesses over 1000 warehouses globally to store the backup parts for their moulds. Its goal is quick maintenance, but most of the parts are seldom used and are stored just in case a part needs replacement. With AM, stocking parts becomes unnecessary because most of them can be printed on demand. A digital file could be created anywhere

Fig. 7. Transformation of supply chain and logistics due to the change of AM product flow.

Table 3
EPI ranking (EPI, 2022).

Country	EPI rank	Score
Denmark	1	77.9
United Kingdom	2	77.7
Finland	3	76.5
Malta	4	75.2
Sweden	5	72.7
Luxembourg	6	72.3
Slovenia	7	67.3
Austria	8	66.5
Switzerland	9	65.9
Iceland	10	62.8
Netherlands	11	62.6
France	12	62.5
Germany	13	62.4
Estonia	14	61.4
Latvia	15	61.1
Croatia	16	60.2
Australia	17	60.1
Slovakia	18	60
Czech Republic	19	59.9
Norway	20	59.3

in the world, prototyped elsewhere, stored in the cloud, and accessed anywhere. With AM, the stock parts only need to be stored in a digital format: AM saves stocking costs and improves efficiency (Michelle, 2018).

The simplification of supply chains is also a great contribution to sustainability. Because AM production is closer to the consumer, there will be less need for packaging and shipping materials, which leads to a more sustainable method of production (Kubáč and Kodym, 2017).

4.3. Strategic planning and control metrics

In terms of recycling culture, the Eco Town Program is a typical case study of local recycling. The concept originally came from Kalundborg, Denmark. Between 1997 and 2005, 26 regions were approved by the local government. The concept is initialized by a plan developed by cities, towns, or business unions to finalize the project by the prefectural government. According to a brief estimation, Eco Town led to a reduction of 96,000 t of final waste and 46,000 t of CO_2 in 2011 across the 26 regions.

A complex product typically cannot be fabricated in one plant in the CM method, and it relies on multiplants to take care of individual components and finally assemble them in one plant, as an umbrella, to complete the upstream supply chain processes. The parallelism of each plant that produces specific components is transparent and dynamic; however, extensive supply chain and logistics processes can be a major burden to the product cost and environmental impacts. As a case study, Boeing and many other large manufacturers measure AM against CM using three key factors: part performance, cost, and lead time. (1) AM can design and prototype parts extremely fast, decreasing lead time. (2) Due to digital manufacturing, the advancement of technologies in AM is more agile and faster than in CM. Based on the convergence effect, reducing AM's cost through new technologies is always feasible. (3) With the advancement of technology such as joule printing, AM can achieve improved speed and cost.

Strategic planning plays an important role in sustainable manufacturing, and population balancing is a priority. Compared to the world average of 36.9%, India has dedicated 60.4% of its land to agriculture (World Bank, 2020b). With the emerging AM technology and governmental plans, this huge amount of land has a great potential for establishing AM facilities in the form of AM home-based or small-to-large-scale enterprises. From the viewpoints of environmental protection and social empowerment, reducing import dependency and increasing domestic manufacturing can reduce the transportation distance and enhance local manufacturing.

Table 4
CO_2 emissions control ranking (EPI, 2021).

Nation	**Rank**	**CO_2 control score**
Azerbaijan	1	99.99
Nigeria	3	95.14
Turkmenistan	4	93.12
Taiwan	5	87.88
Sri Lanka	6	87.1
Myanmar	7	87.09
Switzerland	8	85
Laos	9	84.57
Republic of Congo	10	82.92
Sweden	11	82.47
Liberia	12	82.34
Romania	13	81.24
Macedonia	14	78.51
Rwanda	16	77.66
Malawi	17	76.76
Sudan	18	75.99
Belarus	20	73.1

However, there are various challenges to the related entities, including technical and legal issues for the authorities in regard to implementation. Technically, there is still a lack of understanding of the material properties, process technology, and performance. AM standards and the certification of processes and parts need time and effort to evaluate the accuracy of the parts of the AM domestic industry, surface finish, fabrication speed, volume, and data formats. There is also a limitation in the process, legal and intellectual properties, and monitoring mechanisms (MEITY, 2020). In the case study of India, a strong potential AM market, it produces concerns in regard to the strategic control of human-centric strategy and control metrics.

4.3.1. Sustainable environment

This study applies EPI scores and CO_2 emissions to demonstrate their correlation with population control. The EPI applies the framework to organize 32 indicators into 11 issue categories and two policy objectives, with different weights to produce the total score. Raw data from over 180 nations are applied, which are taken from globally recognized organizations, such as EPI or the World Bank. The statistics indicate an EPI score, as indicated in Table 3 (EPI, 2021), and CO_2 emissions in environment protection, as indicated in Table 4 (EPI, 2021).

As indicated in Fig. 8-a, in the plotting of the EPI score vs. the CIT, the EPI requires a strong economic foundation to protect the environment, so most well-developed countries have an overpopulation problem. Urbanization is inevitable in those nations with strong economic backgrounds, so the appropriate population density of urban areas favours EPI scores because environmental protection requires funds. In addition to the regular statistics, a separate plot divides the statistics into two groups: the higher GDP (equal to or higher than 10,000 USD per capita per year), as shown in the green line, and the lower GDP (<10,000 USD), as shown in the red line. Both the green and red lines demonstrate similar correlations between EPI and CIT overpopulation. In the range of 2000–5000 CIT (persons/km2), EPI demonstrates a high potential for higher than 60 EPI scores, and 2000–3000 CIT can be a golden range to support both the environment and economics. When the CIT is > 5,000, the EPI score starts to drop because overpopulation affects social ecology. When the CIT is < 2,000, the nation has not established a certain level of urbanization or a sufficient economy to support the EPI.

Fig. 8-b and 8-c show correlations of CO2 emissions with RPR and CIT, respectively. Fig. 8-b shows CO2 emissions vs. RPR and demonstrates that a higher RPR (>20%) may support the reduction of CO2 emissions. Fig. 8-c further shows CO2 emissions vs. CIT and demonstrates that a higher CIT (>2500) may produce more CO2 emissions. However, if the nation possesses a higher RPR (>30%), then a higher CIT (in a range of <5000) may prevent the massive accumulation of CO2

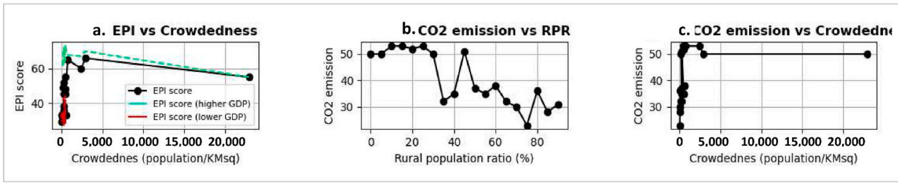

Fig. 8. EPI vs. CIT and CO2 emissions vs. RPR and CIT
Raw data: World bank GDP, 2019; EPI, 2021; City Mayors Statistics, 2020; Worldometers (2021)..

Table 5
Basic statistics of raw data from top 20 EPI countries raw data: EPI, 2022; World Bank (2020a), 2020b.

Country	EPI score	GDP ($)	GDP growth (%)	RPR (%)
Denmark	82.5	61,063.3	−2.3	12
Luxembourg	82.3	116,014.6	−3.7	8.8
Switzerland	81.5	87,097.0	−3.1	26.2
United Kingdom	81.3	41,059.2	−9.9	16.3
France	80.0	39,030.4	−8.1	19.3
Austria	79.6	48,586.8	−7.1	41.5
Finland	78.9	48,745.0	−3.0	14.6
Sweden	78.7	52,274.4	−3.6	12.3
Norway	77.7	67,329.7	−1.3	17.4
Germany	77.2	46,208.4	−4.7	22.6
Netherlands	75.3	52,397.1	−4.3	8.1
Japan	75.1	40,193.3	−4.3	8.3
Australia	74.9	51,692.8	−1.3	13.9
Spain	74.3	27,063.2	−11.2	19.4
Belgium	73.3	45,159.3	−6.2	2
Ireland	72.8	85,267.8	4.6	36.6
Iceland	72.3	59,270.2	−8.0	6.1
Slovenia	72.0	25,517.3	−4.8	45.2
New Zealand	71.3	41,441.5	−0.2	13.4
Canada	71.0	43,294.6	−6.3	18.5
Average (top 20)	**76.6**	**53,935.3**	**−4.4**	**18.125**
Average (200 nations)	**43.5**	**15,751.2**	**−5.6**	**38.281**

emissions because the nation has sufficient space to dilute CO2.

4.3.2. Sustainable economies

GDP and GDPgr are the key indicators of economies used in this study. GDP is a monetary measure of the market value of all the final goods and services produced in a specific time period (year) in a certain location (a country). GDPpc is the national GDP divided by total population, usually represented by USD/person-year. GDPgr measures how fast the economy is growing. The rate is derived by comparing the most recent year of the country's economic output to the previous year. Job opportunities can be a genuine driving force for oversaturated populations. Through the rural development of AM and HBM, unemployment and people who enjoy rural life will have the opportunity to relocate to rural or suburban areas.

Industrialization in surplus rural areas can be critical to economies. Through priority settings and dependency analyses, both CIT and RPR can be critical factors to regulate demography. They align rural or suburban development to AM, resolve the social issues caused by overcrowded conditions, and drive sustainability into a virtuous cycle. By contrast, with the advent of industries and effective land usage, strategic control can be the guideline because economies, society, and the environment correlate under certain conditions and come to support one another (Patnaik, 2018). Usually, a higher GDP means a higher EPI score, lower GDPgr percentage, and lower RPR percentage. This is demonstrated in Table 5, and the data of 2020 are used, which are the most updated data from the World Bank and EPI.

In Table 5, the average values of the top 20 EPI countries are compared to the average values of 200 countries. The possible reasons of the trend among GDP, EPI, and RPR are as follows:

1). If there is an optimization requirement between economies and the environment, particularly when a nation dedicates top priority to economics and neglects the environment, then the sustainable environment will become an obstacle with lots of drawbacks. Conversely, if a well-developed country spends sufficient funds in environmental protection and ecosystems, then ensuring a sustainable environment will not be a problem. This can be a possible reason that most countries with strong economic backgrounds possess good EPI scores.

2). Higher GDP does not guarantee a higher GDPgr, and most of the countries holding a higher GDP score may have a lower GDPgr. One possible reason is that most of the opportunities are saturated. Conversely, penetrating new markets can be relatively tougher than those developing countries possessing higher RPR percentages, providing better opportunities for industrialization and a higher potential for foreign investment.

As illustrated by Fig. 9-a, there is no significant correlation between GDPpc and the EPI score. However, for those nations with a lower EPI scare (<60), as shown in the red dashed line, a rough trend shows that a higher GDP may derive from a higher EPI.

As demonstrated in Fig. 9-b, a well-established country will typically possess a lower RPR percentage than developing countries; however, there is no evidence that a higher RPR (>30%) affects GDPpc because rural development has the same importance for urbanization. This implies that preventing abnormal rural-to-urban migration and relocating overcrowded populations to rural AM businesses are effective solutions to creating sustainable economies and improving the environment. As evidence, Table 5 shows the data of those top 20 EPI ranking countries; the RPR percentages of Switzerland (26.2%), Austria (41.5%), Ireland (36.6%), and Slovenia (45.2%) are in the same level or even higher than the average RPR (31%) or GDP ($13,535) of 200 nations.

Fig. 9-c explains the correlation between GDPgr and RPR. Particularly for developing countries, a low RPR usually affects the GDPgr, which is avoided by developing countries. This phenomenon is still

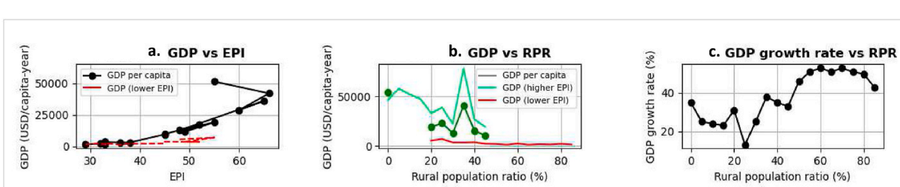

Fig. 9. GDP vs. EPI and RPR and GDP growth vs. RPR
Raw data: World bank GDP, 2019; EPI, 2021; City Mayors Statistics, 2020; Worldometers (2021)..

Table 6
Plastics waste and MRF statistics.

Country	A. Plastic waste (t)	MRF estimated	B. MRF count	Population	Average (kg/ person)
China	59,079,741	295	70	1,444,216,107	40.9
US	37,825,550	189	417	332,915,073	113.6
Germany	14,476,561	72	286	83,900,473	172.5
Brazil	11,852,055	59	102	213,993,437	55.4
Japan	7,993,489	40	388	126,050,804	63.4
Russia	5,839,685	29	285	145,912,025	40
UK	4,925,590	25	331	68,207,116	72.2
Spain	4,709,157	24	100	46,745,216	100.7
France	4,557,128	23	234	65,426,179	69.7
India	4,493,080	22	16	1,393,409,038	3.2
Mexico	3,725,463	19	27	130,262,216	28.6
Italy	2,899,258	14	361	60,367,477	48
Netherlands	2,571,398	13	70	17,173,099	149.7
Malaysia	2,031,675	10	36	32,776,194	62
Poland	1,346,905	7	175	37,797,005	35.6
Canada	1,154,309	6	67	38,067,903	30.3
Portugal	1,022,683	5	63	10,167,925	100.6
Australia	900,658	5	62	25,788,215	34.9
Ireland	715,716	4	29	4,982,907	143.6
Norway	499,682	2	33	5,465,630	91.4
Singapore	359,483	2	17	5,896,686	61

under investigation, and one of the possible reasons is that high RPR may continue attracting timely, more emerging, and larger investments from overseas. The continuity of investments causes exponential growth in GDP; even the current GDPpc is below the averaged RPR.

4.3.3. Sustainable society

The pandemic crisis has been one of the primary societal issues in recent times. Pandemic crises, such as the COVID-19 outbreak, significantly affect society, the workforce, and the population, particularly people living in poverty who are unable to safely shelter in place. The elderly, people with disabilities, refugees, migrants, and displaced persons also suffer disproportionately. Homeless people in overcrowded cities are highly exposed to the dangers of the virus, and the unemployment rate has increased. The virus has taken millions of innocent lives away and damaged the global economic structure. An urban-centric approach does not favour pandemic protections because homeless people contribute to spreading the virus in overpopulated cities, and social distancing becomes a major issue due to infrastructure shortages. To investigate the relationship between the key factors of the COVID-19 pandemic that affect sustainability, this research applied raw data from 200 countries, ranked from 1 to 200 on EPI by Worldometer to analyse the trends among RPR, CIT, EPI, and COVID-19. Demography planning can be an effective method for crisis prevention. It creates job opportunities and better allocate the workforce from overcrowded metropolitan areas to rural ones to support materials recycling and AM businesses. The recycling facility can be the entry point to increasing the recycling rate percentage.

Across the CRM model, MRF capacity is critical to CRM processes because it means that the materials recycling rate percentage and manufacturing yield will drive the scale of the whole CRM. A typical MRF usually can handle 200,000 t/year of plastic waste, and most MRFs can be enhanced to increase this capacity. The MRF count of each country in the list in Table 6 is calculated according to plastic consumption. The “estimated MRF” count is compared to the real “MRF count”. Most countries have a sufficient MRF count to manage plastic waste based on current capacity; however, several countries still have a gap in terms of the satisfactory recycling of plastic waste, and an insufficient number of MRFs means the recycling rate percentage is low.

An understanding of each country’s plastic consumption is necessary before the review of recycling capacity. In Table 6, the statistics data of 2022 indicates that the plastic consumption of each country varies (World Population Review, 2022). From the viewpoints of plastics recycling capacity, China has significantly fewer MRFs than estimated, and India has a marginal number of MRFs compared to its estimate. Conversely, Germany, and Netherlands consume a high volume of plastics, which needs to be reduced through changing consumer behaviour. Canada, and Australia consume less, so their MRFs are very sufficient, which can provide efficient sorting services in ultimate optimization (ENF, 2022). Consequently, the authorities can fully utilize their overcrowded populations to realize sustainable manufacturing towards “zero waste” objectives.

To envision CIT and its impacts, Table 7 demonstrates the CIT of sample countries (City Mayors Statistics, 2020), and India ranked top in CIT. The serious overcrowded conditions in major cities such as Mumbai and Delhi, all with over 10 million residents, mean they do not have sufficient land area to accommodate appropriate social distancing, which is one of the reasons the virus has spread so rapidly. The CIT of Japan is marginally approaching 5,000, whereas New Zealand is perfect, and their COVID-19 cases are low (Worldometers, 2021).

Fig. 10-a demonstrates the correlation between COVID-19 and EPI score. The results are not as expected because those countries with a high EPI score do not have better pandemic protections. In contrast, the COVID-19 case rate increased with the increasing EPI score. A possible reason for this, as indicated in the EPI vs. GDP analysis, is that a higher EPI score is usually contributed by an awareness of environmental sustainability and strong GDP, whereas those countries with a strong economic background usually come with higher interpersonal interactions and social activities, which can help spread the virus. The results also reveal that those countries possess strong environmental protection capabilities, which does not mean they can effectively mitigate pandemic crises.

Fig. 10-b shows that a CIT of >5000 can negatively affect COVID-19

Table 7
CIT sample data for three nations in illustration (City Mayors Statistics, 2020; Worldometers, 2021).

City/Urban area	Country	Population	Land area (km.sq)	Density (people per km.sq)	COVID-19
Sydney	Australia	5,180,000	1687.0	3070.5	2532
Melbourne		4,260,000	2080.0	2048.1	
		Total population	Total land	CIT	
		9,440,000	3767.0	**2506.0**	
Mumbai	India	2,597,000	484.0	53,657.0	24,771
Delhi		25,830,000	1295.0	19,945.9	
Bangalore		9,920,000	534.0	18,576.8	
Chennai		8,880,000	414.0	21,449.3	
Hyderabad		8,610,000	583.0	14,768.4	
		Total population	Total land	CIT	
		79,210,000	3310.0	**23,930.5**	
Tokyo/Yokohama	Japan	37,280,000	6993.0	5331.0	13,726
Osaka		11,530,000	2564.0	4496.9	
		Total population	Total land	CIT	
		48,810,000	9557.0	**5107.3**	

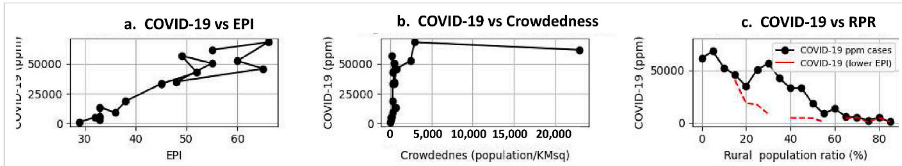

Fig. 10. COVID-19 vs. EPI score and COVID-19 vs. CIT and RPR
Raw data: World bank GDP, 2019; EPI, 2021; City Mayors Statistics, 2020; Worldometers (2021)..

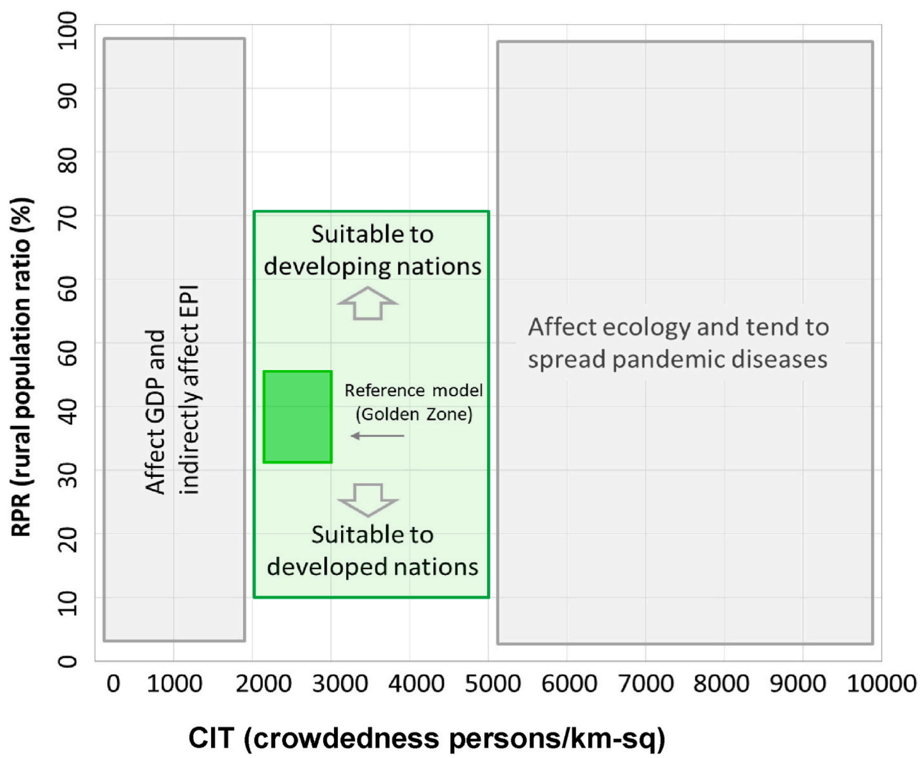

Fig. 11. Control metrics of RPR and CIT and Gold Zone.

spread, and a CIT of <3000 is recommended. Fig. 10-c suggests higher RPR can be an effective method for preventing virus spread. However, because a high RPR does not favour GDP, a 10–50% RPR can be a suitable control. This may not be applied to developing countries because GDPgr can be even more important to those developing countries; in general, an RPR of >20% can be an appropriate control to optimize the economic, social, and environment factors.

4.4. Data analysis and results

In the range of 2000–5000 CIT (persons/km2), a >60 EPI score can be easily achieved because when CIT is > 5,000, overcrowded conditions can negatively affect social ecology and pandemic protection. When CIT is < 2,000, less urbanization may lead to weak GDP and weak support of EPI. In general, the CIT of a nation is suggested to be controlled in the range of 2000–5000 to protect the environment and support the economy.

A high RPR does not favour GDP, so a 10–50% RPR can be suitable, and this may not be applied to developing countries with an RPR that is even higher than this range. GDPgr can be even more important to developing countries. Through the trend analysis, this study proposes an optimized solution that involves an RPR range of 30–50% with a CIT of <5000 to enhance pandemic protections and create a better EPI and GDP though an optimization process. If the nation possesses a higher RPR (i.e. an RPR of >30%), then a higher CIT that is under 5000 can still prevent a massive accumulation of CO2 emissions due to population issues.

4.5. Control metrics setup

In summary, RPR and CIT are the key factors of the control metrics that affect sustainability. An extensive investigation reveals that AM is a good standpoint for sustainable manufacturing because of its reduced reliance on supply chain management and logistics. This suggests AM will become an industry standard if the human factors can be appropriately addressed and the weaknesses in scaling and speed can be resolved.

Strategic planning applies control metrics as a foundation of AM in optimization among the environment, economics, and society. Due to the interferences among these three factors, any missing item or weakness in any aspect can significantly affect AM's leadership role in terms of sustainability. As indicated in Fig. 11, for developed countries, overcrowded conditions should be avoided. In general, a 2000–3000 CIT and 30–50% RPR are the golden range. However, each nation needs an assessment based on its situation and a tailored strategy to determine the best-fit control metrics before deployment.

5. Limitations

This research aims to achieve sustainable AM manufacturing in the

Table 8
AM roadmap and limitations.

Strategy	Solve the quantity issues first, and then shift the focus to quality and standards			
Human factors	Workforce ⇨	Technologies ⇨	Control metrics ⇨	Standardization
Objectives	Allocate workforce	Scaling & speed	Strengthen localization	Manufacturing mainstream ⇧
Strategic control	Strengthen human-centric factors to solve scaling and speed issues as well as industry standards			
	Strengthen tactical factors for a solid foundation of sustainable manufacturing			
Assessment results	Localization ⇨ Less reliance on supply chains ⇨ Reduce transportation is feasible to AM ⇩			
Previous studies (quantitative)	Evaluation of energy consumption, transportation, CO_2 emissions, cost, materials yields			
Previous studies (quantitative)	Prototyping, lead time, easy entry, scaling, speed, complexity, flexibility			

plastic industry, and the strategic control model is proposed to fill in the gap between the existing models and the goal. However, there are still limitations that need further study, such as the three aspects of sustainability. This study ensures the AM sustainable manufacturing does not cause any negative impact to sustainability instead, the model brings-in advantages to sustainable environment, economies, and society simultaneously. However, as sustainability is a big scope, it requires multi-disciplines investigation, and it shall not be in the scope of this study. In addition, other areas such as applicability of the model, the standards, and the control metrics are new areas that need separate studies.

AM materials have large anisotropy and a variety of technologies, materials, and applications. With different AM technologies, parameters and standards are crucial to guiding development. To make the products more reproducible and reliable, standards need to be in place (Dizona, 2018). Standards refer to technical methods, processes, specifications, and definitions with respect to a system on which there is general agreement, as promulgated by recognized standards organizations (Clark, 2017). To drive the global standard, ASTM International formed the F42 Committee in 2009 for AM Technologies. ISO created its ISO/TC 261 Committee in 2011 to ensure AM standards development, and ASTM and ISO jointly agreed to develop global standards.

To solve the standardization issue, AM needs more global activities and testing standards to engage more entities. Global authorized organizations have to aggregate fragments into consolidated specifications in a sharable platform, strengthen their foundations, and make AM standards concrete and transparent. This leads to cost, effort, lead-time savings, CO_2 emissions reductions, and risk declines to further ease AM's burden, shifting AM's focus to the standardization of technologies, processes, and applications.

From the applicability perspective, this study recommends an RPR of 10–50% and a CIT of <5000 as general guidelines, and the golden range control includes a 2000–3000 CIT and a 30–50% RPR, though these may not precisely meet individual requirements. Each nation can apply the cost pattern as a method with individual trends, historical data, and strategy to produce their RPR and CIT control metrics. Each nation needs to apply control metrics to optimize the scalability and speed requirements of AM.

For the time being, the AM industry requires a collaborative pattern and a common practice to connect large enterprises, SMEs, and HBMs to fully utilize its natural advantages through localization and distributed manufacturing. However, global organizations need to share CIT and RPR control metrics as well as their associated indicators, such as GDPpc and EPI, for optimization purposes. Therefore, the strategic control model can effectively optimize the maximum effects of control against performance in GDP, GDPgr, EPI, and pandemic protection. Further investigation will be continued in a separate study.

In the AM roadmap demonstrated in Table 8, the strategic control model can strengthen the tactical factors, such as localization, supply chains, and transportation. It is expected to enable AM capabilities in the workforce, technologies, control metrics, and standardization. However, because control metrics and standardization require longer times and more foundations, workforce and technologies will be enabled first to streamline the roadmap.

6. Conclusions

Sustainability has become one of the top missions of this decade. A disregard of any sub-discipline of sustainability can destroy the lives of millions. For this reason, sustainable manufacturing is critical to all aspects, including the environment, economy, and society.

Transportation is identified as a key factor that affects sustainable manufacturing, and localization is an effective method to minimize the impacts. A strategic control model realizes the localization of AM through workforce allocation and HBM. This can eliminate the reliance on supply chains and can reduce transportation costs by up to 25-fold in AM processes and the associated CO_2 emissions by a similar figure.

The novel model further applies strategic planning and control metrics to normalize demography and relocate overcrowded populations to rural areas to support AM. In addition, it builds an AM society and HBM to solve the scaling and speed issues. The model further proposes a specified range of CIT and RPR to optimize the key indicators of EPI, GDPpc, and GDPgr to support sustainable development. In general, a 2000–3000 CIT and a 30–50% RPR are the optimized golden range. The applicability of the golden range may not precisely meet individual needs; therefore, each nation needs to apply historical data and individual strategy to produce appropriate control metrics.

A strategic control model can ease many AM bottlenecks, such as scale, speed, and traceability. It provides a good opportunity to position AM as an industry mainstream and to shift AM's focus, shedding more light on the appropriate standards and technologies once the basic requirements are achieved.

CRediT authorship contribution statement

Haishang Wu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hamid Mehrabi:** Conceptualization. **Nida Naveed:** Conceptualization, Supervision, Validation, Writing – review & editing. **Panagiotis Karagiannidis:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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