WHITE PAPER

SUSTAINABLE MANUFACTURING

Driving sustainability through Industry 4.0 principles, framework & technologies

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Table of Contents

Chapter 1: Introduction

Sustainability is at the forefront of corporate minds, ranking as one the most important current business objectives, yet only half say they are effective in achieving environmental sustainability objectives. With a target date of 2044, nearly three-quarters have set a net-zero goal; however, only 35% have taken actions on a sustainability strategy1. In this paper, the focus is how manufacturing impacts sustainability and how it can execute both supportive of sustainability while improving manufacturing in a manner that encompasses the realms of People, Planet and Prosperity. Because managing manufacturing operations in an environmentally and socially responsible manner – "sustainable manufacturing" – is no longer just nice-to-have, it has become a business imperative.

Sustainable manufacturing is a holistic concept that seeks to balance social, economic, and environmental performance - People, Planet and Prosperity. The long-term success of a company relies on all three dimensions of sustainability. These three pillars integrate different viewpoints of enterprise sustainability. Today, little doubt remains about the correlation between improved sustainability practices and better financial results. Companies that are committed to sustainability and manufacturing are increasingly efficient, use fewer resources, create less waste to generate more revenue, and produce higher returns on investment. Sustainable manufacturing has matured as an important strategic and operations objective to increase growth and global competitiveness. Seventy percent (70%) of millennials would prefer to work in a company with a strong sustainability agenda. The number of businesses and public sector organizations committing to reaching net zero emissions has almost doubled in less than a year. Businesses are now looking beyond electricity consumption and taking a wider view across the whole lifecycle.

While manufacturing industries are clearly investing in sustainability, sustainability goals and associated metrics are typically developed at a corporate level, often without any specific, actionable requirements for plant personnel. Therefore, plant operators, technicians, and subject matter experts (SMEs) do not have the insights they need on the process data to implement improvements. As a result, developing measurable sustainability key performance indicators (KPIs) to improve outcomes is nearly impossible in present environments. Due to the lack of insight into their process data, most sites only focus on environmental and social governance reporting and compliance as metrics for their success. Operators thus focus on monitoring a single indication of environmental performance (i. e. emissions levels), and SMEs spend many days a month wrangling historical data to simply document compliance. If an environmental violation does occur, corrective actions are only taken after the event, and there is a lack of insight to determine what caused the problem. In short, without the right analytics tools, organizations are, at best, reactive to a site's environmental impact, and at worst oblivious. Hence, there is a need to strike an acceptable balance between operations metrics and business metrics. The industry should look beyond macroeconomic indicators covering environmental, social, and economic aspects of sustainable development, that affect society in the long run. This can be only achieved by a holistic vision that meets the needs and aspirations of all the stakeholders. This has led to the need of an integrated, holistic conception of sustainability in manufacturing capable of incorporating vision that meets the needs and aspirations of all the stakeholders and supports an organizational vision. This approach can be used in a flexible way, where it links the three conceptual dimensions and the relationship between them strives to harmonize the development of a sustainable enterprise.

Our postulate is that all three (People, Planet and Prosperity) dimensions, as shown in Figure 1, when designed together in harmony, can achieve the results through careful planning and leveraging the available Industry 4.0 principles, frameworks and tools, with mobile, IoT and cloud ranking as the most important technologies for advancing sustainability objectives2.

Figure 1: Three Pillars of Sustainable Manufacturing

Dimension	Manufacturing's path to achievable sustainability
People	In the measurement of people, the key areas are: • Safety, Health, Ergonomics, Competency, Skills, Work Life Balance, Work Environment The effectiveness and well-being of employees are taken into consideration through these as both art of the design and solution execution.
Planet	To measure planet, the goal is to encompass all areas of positive impact in the following areas: • Clean Water, Clean Air, Recycling, Waste Reduction, Circularity, Clean Energy By these measurements, we can then ascertain the impact of our design and execution of the principles of sustainability on the planet and understand more thoroughly how our approach will impact positively.
Prosperity	The measurement of prosperity is considered a responsible path for a company to provide a clean, sustainable solution and deliver prosperity for the company objectives. Below are the focus areas to measure for this objective across the value chain: • Engineering Efficiency, Supply Chain Efficiency, Manufacturing Efficiencies (Operations, Maintenance Efficiency, Information and Energy), Service Efficiency While measuring prosperity may seem counterintuitive to the mission of sustainability, it must go hand-in-hand to ensure the organization does not struggle during the transformation process and smart investments are made with regard to the vision of a green planet.

Table 1: Three dimensions of sustainable manufacturing

Thus, this paper presents a broad conceptual framework based on three primary indicator sets that are proposed under People, Planet and Prosperity. Collectively these will provide guidance to manufacturing enterprises in setting targets for sustainable development and on-going monitoring their implementation. There have been some efforts on these three indicators to define the content and scope of the notion of sustainability, each from its distinct perspective. The formation of such a holistic approach for manufacturing requires the structuring of a set of basic principles to serve as its foundation. This paper explains what to prioritize to assess environmental sustainability at the organizational level and it covers identification, definition, selection, and composition of environmental KPIs to provide guidance for the industry.

Chapter 2: Manufacturing Industry Transformation

The manufacturing industry is transforming. Three separate trends, including Climate Change, US SEC Disclosure, and Paris Accords, are shaping the move to "greener" initiatives of which manufacturing will have a role.

Climate Change

Climate change has become a particularly thorny topic in terms of the politicization of both the severity and solution approach to global warming. It is undeniable that climate change is both real and impactful. The chart below shows to number of weather-related events that have occurred since 1980 and while cause is debated, the trend depicts an increased in weather related event.

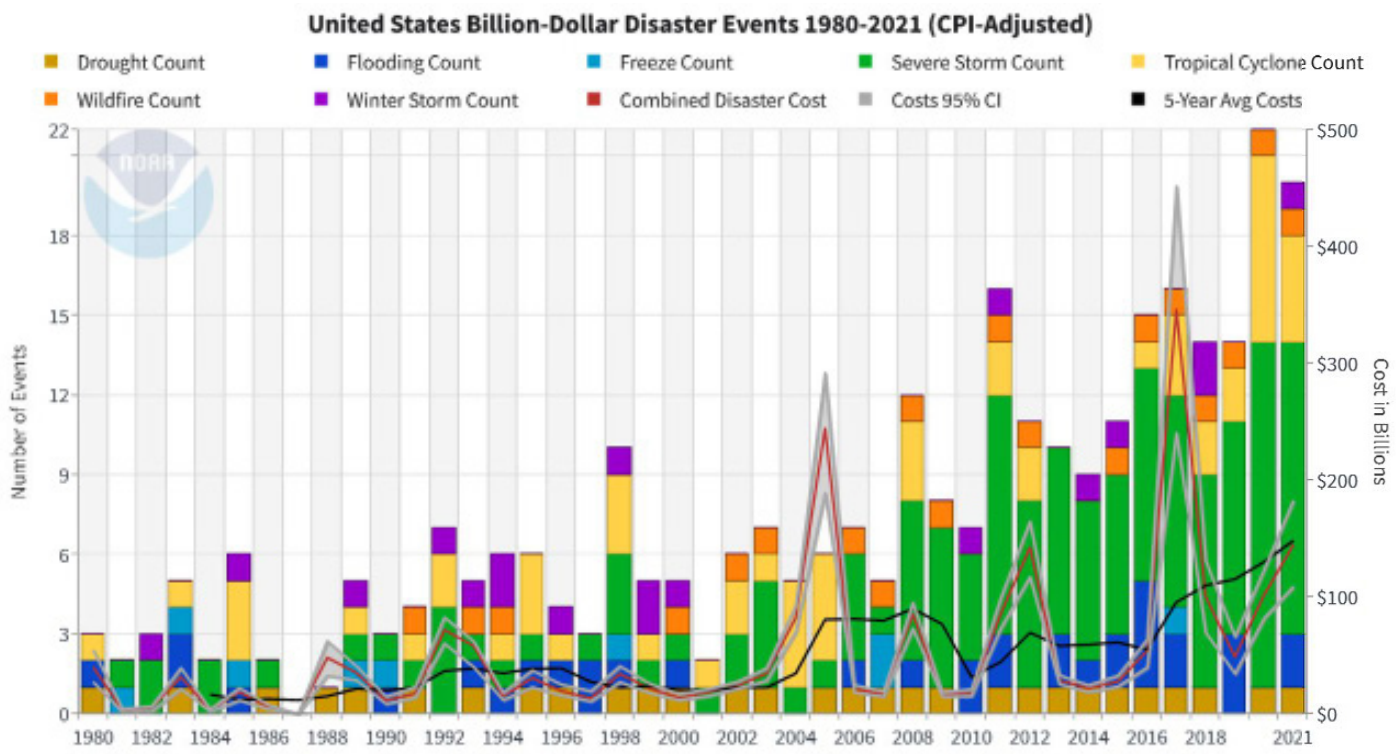


Figure 2: United States Billion-Dollar Disaster Events (CPI - Adjusted)

Following can be inferred from figure 2:

- **Billion-dollar weather disasters on the rise:** Not just due to higher frequency of extremes but also due to more population in vulnerable areas.
- **Good News:** Loss of life per disaster drastically lower.
- **Bad News:** Monetary loss drastically higher.

US SEC Disclosure

The US SEC is proposing rules to enhance and standardize climate-related disclosures for Investors. This change has a direct impact of reporting and can be one of the larger watershed moments to start the transformation of manufacturing.

This will drive the following:

- Physical risks of your assets from climate change
- Your company's contribution to climate risk with greenhouse gas emissions
- How transformation to net zero emissions affects your business

Paris Accords

Sustainability goes beyond the US SEC and extends to other world leaders who are driving sustainability. In 2015, hundreds of nations across the globe adopted the Paris Agreement – a legally binding international treaty on climate change. Its goal is to limit global warming to well below 20Celsius, preferably to 1.5°Celsius, to help avoid the most severe impacts of climate change. To achieve this long-term temperature goal, nations must drastically reduce global greenhouse gas emissions & work together to address this challenge. Sustainable development goals (SDGs) were established by the UN as part of the Paris Agreement and set out 17 objectives to eliminate poverty, improve education and health outcomes, create better jobs and tackle our key environmental challenges by 2030.

Figure 3: UN's Sustainable development goals

Approach

While some of these initiatives have political connotations and special interest motivations, the overall impact and movement of the world to a cleaner, sustainable environment is undeniable. As a result, manufacturing companies must look to change sustainability ambition into action. These follow the following chart, as shown in Table 4, to help drive an organized approach to those ambitions.

Aligned Business Strategy	Organization, operating model, culture, data and tech strategy to drive innovation across business and society
ESG Data, Reporting, and Climate Risk Management	System of record to operationalize sustainability goals and environmental intelligence

Intelligent Facilities and Assets	Resilient IT Infrastructure	Circular Supply Chains
Operational insight to drive clean energy transition, efficient waste management, and decarbonization	Responsible computing to enable sustainable IT and drive social impact	Intelligent workflows for equitable, transparent, and net zero supply chains

Figure 4: Organizational approach to sustainability ambitions

The first two areas focus on the strategy (and governance) of the organization to align to this new way of thinking and setting the ability to report results based on both standards (a mixture of regulatory) and company ambition based on the unique market positioning and branding required.

Chapter 3: Defining Sustainable Manufacturing

Manufacturing companies face increasing pressure to improve the sustainability in their operations. However, beyond reduce, reuse, and recycle programs, little guidance is available to help manufacturers minimize their environmental impacts. The reason is because manufacturers explore what to measure for improvements to the overall sustainability of their products and manufacturing processes. Therefore, the need for an open, inclusive, and neutral procedure in selecting KPIs for sustainable manufacturing has been increasing.

Sustainability metrics are quantifiable metrics in the creation of manufactured products through economically strong processes that minimize negative environmental impacts while conserving energy and natural resources. The traditional practices of managing KPIs along with their efficiency and effectiveness are proving to be ineffective when used in the context of overall sustainability. It is essential that the manufacturing KPIs for maximizing impact and manufacturers are keen to determine what to measure to improve overall sustainability of their products and manufacturing processes. Majority of the manufacturing indicators are defined for prosperity (availability, performance, quality) and to measure economic outcomes (at asset or process level) and a harmonized enterprise-wide sustainability indicator is largely missing. It is difficult to understand and select specific indicators from many available stand-alone indicators. There is a need for an open, inclusive, and neutral procedure in selecting KPIs for sustainable manufacturing. Hence, it is essential to analyse the characteristics, indicators, limitations, benefits, and conclusions of metrics on industrial sustainability to propose a set of generic sustainability indicators for industrial organizations. Manufacturing organizations need better statistical 'compass' to shift emphasis from measuring economic outcomes to measuring sustainable performance. This paper presents a procedure for manufacturers to prioritize the KPIs for measuring, monitoring, and improving environmental aspects for manufacturing processes.

These metrics track and review the progress of an organizations' sustainability journey. It is difficult to understand and select specific indicators from many available stand-alone indicators. Hence, it is essential to identify the right metrics and define the process to measure those metrics. This approach for organizations to select KPIs for measuring, monitoring, and improving sustainable manufacturing and has been adopted to establish the Sustainability KPI's in terms of the three main pillars of people, planet, and prosperity.

- First, the sustainability objectives (goals) of the main pillars were defined.
- Second, the initial KPIs for the respective pillars were identified. These KPIs were validated with industry practices and derived accordingly.

1. People

The people aspect of sustainability in manufacturing practices focusses on the human factor in manufacturing. This includes consideration of relevant human factor issues in advancing manufacturing operations and processes from the point of view of the well-being of the people. On the other hand, external social sustainability should take care of corporate social responsibility and its social impact on its external stakeholders. The idea is to bring everyone together physically, but also online. This brings people closer and allows people from different units, who would not normally work together, to collaborate and ensure that the tacit knowledge flows throughout production and increases work motivation and in turn, well-being. It's therefore really an ideological shift as well, where all human beings can fulfil their potential in dignity and equality and in a healthy environment. This also brings a key competitive advantage when worker's wellbeing is ensured on a sufficient level. When social sustainability is taken care of it pays itself.

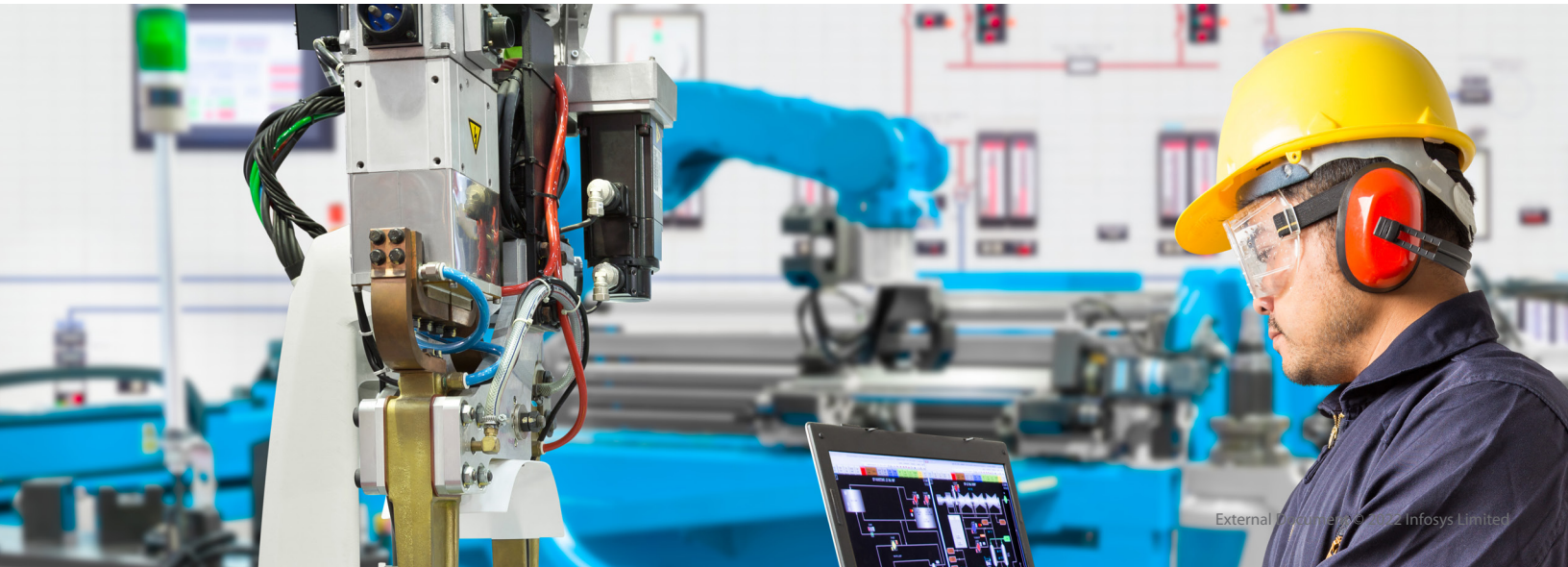
Therefore, on corporate level people aspects of sustainability is realized in concepts such as preventive occupational health and safety, human-centered design of work, individual and collective learning, employee participation, workplace well-being and work-life balance. The promotion of workplace well-being in the framework of sustainable development can be seen as a challenge and opportunity for organizations to achieve goals such as 'the ability of future generations to meet their needs'. The goals and probable KPIs for people dimension are illustrated in Table 2.

People Dimension				
Goals	Employee's acceptance of organizational change	Guarantee the quality of environmental and work condition	Guarantee the respect of the human rights	Participate at the social initiative and to maintain a high level of responsibility
KPI	• Employee satisfaction rate • Employee turnover rate • Percentage of employees as share holders • Employee support (physical activity, healthcare, and medicine) • Employee well being	• Employee satisfaction rate • Employment rate • External/internal relation rate • Employee demographic information – Diversity & Inclusion • Opportunity rate • Number of safety related incidents (per month) • Types of safety events	• Conflict labor rate • Number of human resources incidents • Social security rate • Consumer, supplier and employee safety rate	• Company charity donation rate • Number of social initiatives at national and local level • Total expenses of community initiatives • % Participants in community initiative

Table 2: Goals and KPIs- People Dimension

2. Planet

Whenever an industry builds a new facility or utilizes its supply chain, it has negative consequences to environment. Manufacturing industries have been credited as a key contributor to climate change since the industrial revolution began, yet they can also greatly influence a positive shift by adopting planet friendly measures. Eco- conscious consumers have shown strong inclination towards purchasing products from industries with a sustainable outlook. Many industry leaders are now recognizing their responsibilities and looking for opportunities to reduce the carbon footprint. There is no dearth of innovative ideas that would directly or indirectly help reduce resource consumption, emissions, waste and parallelly streamline processes to increase productivity. Net zero emission needs to become the ultimate goals for manufacturing industries. The goals and KPIs of planet dimension are shown in Table 3:



People Dimension				
Goals	Reduce gas emissions	Improve the use of renewables	Reduce natural resources consumption	Reduce waste and improve the effort to address greenness
KPI	• Emission of ozone depleting substance rate • Emission of greenhouse gases rate • Carbon footprint rate • Sulfur dioxides Emissions • Nitrogen oxides emissions • Percentage of emission of other environmentally affecting gases	• Percentage of waste generated per thousand product units • Dangerous waste generated rate • Percentage of hazardous material over total waste • Percentage of reusable/ recycled material • Percentage of waste recycles off/on site • Waste reduction rate • Percentage of waste reused off/on site • Percentage of pollution indicators	• Energy consumption rate • Electricity consumption rate • Gas consumption rate • Soil usage rate • Water usage rate	• Renewable energy rate • Reusable material rate • Renewable energy rate • Renewable electric sources rate • Sustainable water usage rate • Percentage of energy reduction in product manufacturing • Percentage of recycled material provided by suppliers • Percentage of recycled material used in product development

Table 3: Goals and KPIs- Planet Dimension

3. Prosperity

The healthy economy of an organization ascertains the healthy performance, thus the profit the organization earns. This dimension of sustainability is sometimes confusing as some intuitions do not support the notion that sustainability and profit can run in parallel. It is not sustainable to have maximizing profit as the only criteria while defining organizational strategy. Instead, it is imperative for industry leaders to bring environment friendly initiatives into their strategy which would ensure sustainable growth without hampering the financial performance.

Prosperity Dimension				
Goals	• Increase return on investment • Increase efficiency and productivity with process automation • Reduce labor costs • Improve yield • Reduce risk of business disruption and associated costs • Reduce waste	• Increase the revenues associated with sustainability dimensions • Extend the life of critical assets • Drive better decisions across enterprise • Optimize repairs and inventories • Add efficiency to manufacturing and reduce waste	• Enhance technology process • Increase visibility and proved new insights into operations • Optimize business performance • Increase accuracy and consistency across enterprise with streamlined operations	• Guarantee quality process standards through certification • Improve customer satisfaction • Increase collaboration • Improve quality visibility • Document a product trail for quality improvement
KPI	• Cost of ownership linked to energy, cost of consumption, environmental tax • Growth of grass margins • Investments pertaining to environmental protection • Environmental cost savings • Environmental penalties	• Additional revenue % • Additional price % • Income from recycling and circular economy • Sustainable innovations rate	• Environment friendly product development (%) • Response to environmental programs rates for suppliers • Amount of environmentally safe alternatives	• Production sites with environmental certifications • Environmental information accuracy rate • Environmental information availability rate • Supplier rejection rate • Cost of quality

Table 4: Goals and KPIs- Prosperity Dimension

Alignment with Current Industry Benchmarks

Sustainability has close relevance to quite a few industry standards in practice. Norms are created because of implementing these standards across industries, resulting in the identification and mitigation of inefficiencies. Standardization, in turn positively influences the sustainability initiatives by reducing environmental impact and improving productivity. The defined KPI's are in line with the global standards and benchmarks defined by the industry. These standards include:

- ISO 9001:2015 Quality management system
- ISO 14001:2015 Environmental management systems
- ISO 50001:2011 Energy management systems
- UNE 166002:2014 Research, Development & Innovation management systems
- OHSAS 18001:2007 Occupational health and safety management systems
- ISO 26000 Social responsibility
- SDG Sustainable development goals

Chapter 4: Sustainable Manufacturing Implementation

Industry 4.0 principles, framework and best practices can provide a strong foundation to achieve sustainable manufacturing, meeting all the objectives from people, planet, and prosperity. Sustainability practices such as the circular economy, green cloud computing, and energy monitoring can get benefited from Industry 4.0 technologies1. These technologies aid process integration (human-machine and shopfloor) and lead to economic and environmental sustainability, automation, and process safety. Industry 4.0 technologies positively impact economic outcomes (costs, flexibility, productivity, etc.) and increase the operational efficiency by reducing costs and waste, improving equipment efficiencies, and reducing energy consumption and production waste, and improving product quality. Additive manufacturing reduces the consumption of raw materials with Internet of Things (IoT) embedded in sustainable supply chains. IoT will help coordinate logistics operation to customer demand and make the whole process more flexible. Industry 4.0 also supports process optimization and positively contribute to environmental sustainability performance with efficient resource usage. Digital twin enables visual design and simulation, supporting product and production design along the supply chain and helps reduce quality and resource consumption. Virtual and augmented reality and other assistance systems support workers and reduce repetitive and dangerous tasks, leading to stress reduction and higher satisfaction. Wearable technologies and smart glasses make workplaces safer performance/practices, improved working conditions, working hours, skills, health, and safety.

While the adoption of Industry 4.0 technologies can help achieve more sustainable manufacturing opportunities, these outcomes are not a given. In other words, to achieve sustainability with Industry 4.0, the people behind the manufacturing processes must want to achieve sustainability results. Industry 4.0 is not inherently sustainable, and as through reviewing each of the four Industrial Revolutions, technological advancements often have negative rebound effects. To achieve sustainable manufacturing with Industry 4.0, the perspectives surrounding the relevance and reality of these topics must be understood. Acatech Industry 4.0 maturity index2 provides a holistic and structured implementation approach for sustainable manufacturing utilizing structuring forces namely Resource, Systems, Governance & Processes and Organization Culture.

Chapter 5: Key Recommendations

In the manufacturing business, the inherent issue is how to produce goods while reducing carbon output and reducing waste to achieve sustainability. This thought process permeates the entire value chain from product design, supply chain to product in the field. All the processes required in the value chain can participate in a sustainable strategy and contribute to the "greener" environment. By looking at the entire Value Chain and having an executable sustainability strategy, several sustainability opportunities emerge. The approach taken is to examine the strategy through the following:

People

The focus with People is ensuring buy-in to a sustainable strategy from employees, government, and customers. The key goal in this space is around employee acceptance particularly with the work environment and condition; respect to human rights which becomes both a branding and ESG reporting output which leads to the social responsibility messaging for the company.

Planet

Central to a sustainability vision is responsible manufacturing that focuses on both carbon reduction and sustainable processes. This can be in the form of reduced gas emissions, a commitment to leveraging recycling in terms of renewables leading to a reduction of the consumption of natural resources where possible and reducing waste to improve the "green-ness" position of the company and brand.

Prosperity

The company financial health must always be considered as a component of a transformation of this complexity to ensure a successful conclusion while ensuring the company remains financially healthy while executing this transformation. The key components of this should be return on investment which can broadly be broken down by reduction of cost through both efficiency and waste reduction, and an increase in revenue through branding and perhaps new markets and/or products. When one considers the entire Value Chain in a product lifecycle, such as:

- Product Design
- Raw Materials
- Components (Tiered suppliers)
- Manufacturing
- Supply Chain
- Field Support

The opportunity to create a positive impact has many entry points and opportunity. The approach should entail a crawl, walk, run mentality and each effort should have an outcome and business case defined. The efforts should include data, insights, security, and operational continuity. These thought processes can be considered in new models.

New Business Models

With the overarching thoughts of reusability and recycling, below are key areas of focus with the three points of inspection and solution. These areas hold the promise of leading toward goal achievement of the vision of sustainability on terms that can improve the company through a planned and profitable way.

- Intelligent Facilities and Assets
  - Zero Down-time
  - Zero Defects
  - Clean Energy
- Connected Data Sources
  - Data Fabric
  - Interoperability
  - Security
  - Insights
- Circular Supply Chains
  - Recycling
  - Material Reuse
  - Responsible Design

Value Proposition

The value that sustainable manufacturing can bring include

- Holistic approach
- A human-centric approach
- Closed loop/ circular processes
- Develop a higher degree of robustness
- Comprehensive and globally shared view
- Future-proof, resilient, sustainable, and human-centric.

Chapter 6: Conclusion

Sustainability in manufacturing is an achievable vision and viable when enabled with Industry 4.0. Improving the planet through waste reduction, sustainable energy use, and reusable materials, including recycling, combined with investing in the human element, all while remaining profitable, is challenging but attainable; however, the vision requires guiding principles and continuous improvement to execute the vision.

Success begins with establishing guiding principles to direct the program and allow for corrective action. First, an end state must be defined, which is established based on the principles defined by Planet, People and Prosperity. This end state should leverage tools such as zero defects and waste, zero downtime, along with other Industry 4.0 capabilities across the ecosystem. Considerations should be made for design with recycle materials, a circular economy in product lifecycle and finally, a strategic plan for workers. Industry 4.0 also has capabilities to support worker safety and support digital manufacturing inherent in PLM tools. When leveraging these tools and the execution of the sustainable strategy, the desired outcomes are achievable. Figure 5 depicts the strategy profile to foster thought processes and execute for success.

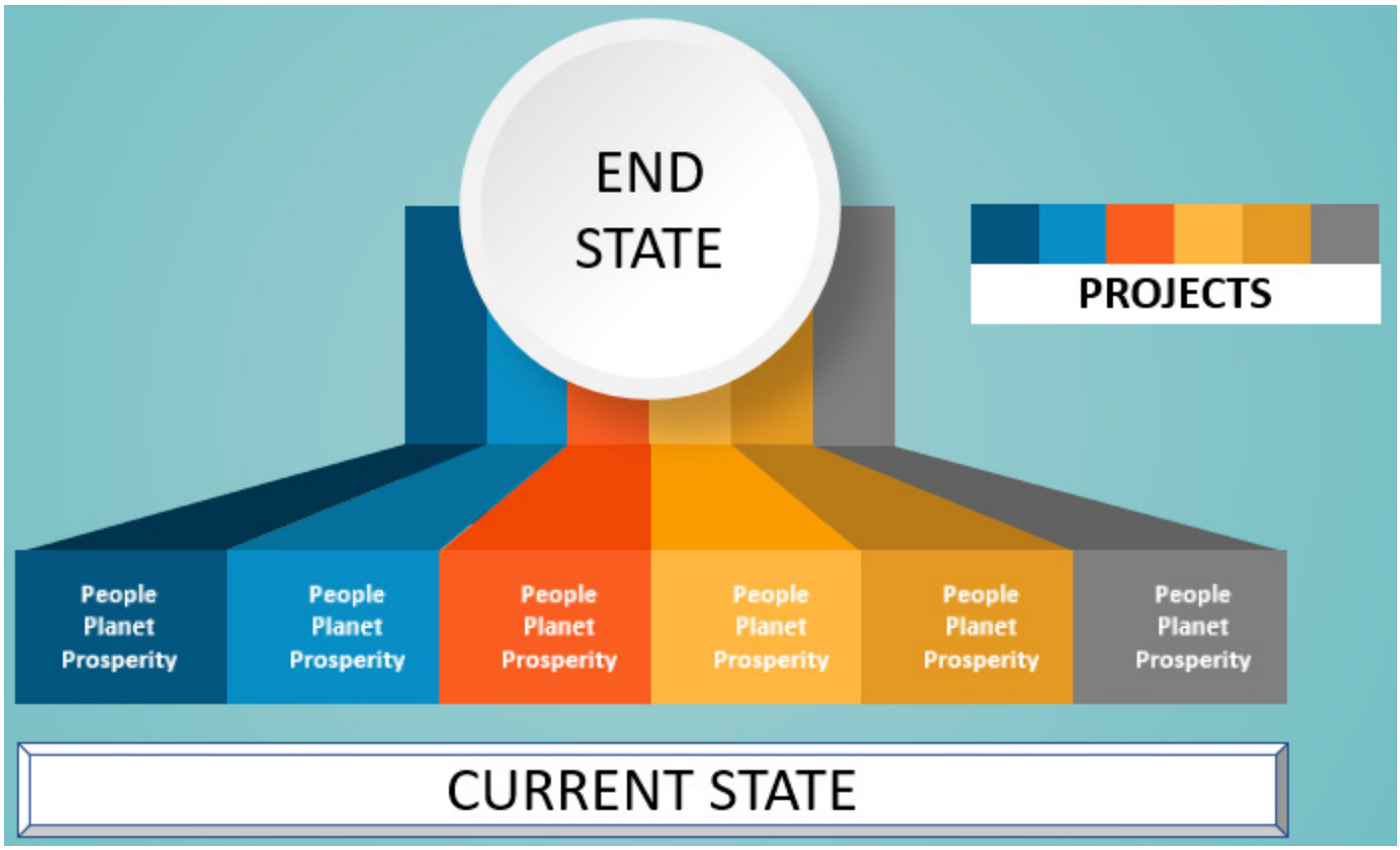


Figure 5: Strategy profile to achieve success in sustainable manufacturing

KPIs keep these objectives at the forefront of decision making allowing for accurate assessment and initiate corrective action if needed. This paper has provided a snapshot of KPIs which need to be evaluated for fit and adjusted if or when the measurements do not fit the stated goals created. KPIs are also a key element in the sustainable manufacturing journey and very important to both track and acknowledge progress across operational data for buildings, people, products, waste, water, and more.

The value proposition provided herein brings the promise of improved business outcomes and the ability to achieve the maximum value of Industry 4.0 to build a robust and sustainable enterprise. People, Planet and Prosperity, when designed together in harmony, can achieve the end results through careful planning and leveraging the available Industry 4.0 tools.

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Dr Ravi Kumar led many innovations and applied research projects for more than 25 years. His areas of expertise include mechanical structures and systems, composites, artificial intelligence, robotics, autonomous systems, AR, VR and Industry 4.0. He is involved in the development of commercial products like AUTOLAY, Nia Knowledge and KRTI 4.0. He contributed to many Industry 4.0 implementation projects and played a key role in the development of Industry 4.0 maturity index under the umbrella of Acatech, Germany. He is involved in design and development of many advanced robotics and autonomous systems including India's first autonomous golf cart. He is a member of the HM-1 and Chair of G-31 technical committees of SAE International contributed to aerospace standards development. He has published over fifty technical papers and holds five patents. He has a Ph.D. and an M.Tech in Applied Mechanics from IIT Delhi, and a BE (Honors) from BITS Pilani, India.

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