LEAN MANAGEMENT, DIGITAL TECHNOLOGIES

Sustainable Industrial Performance through Lean Management, Digital Technologies, and Resource Optimisation in Australia's Manufacturing Sector

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Abstract

Australian manufacturers are expected to raise productivity while cutting waste, energy use and emissions, yet the country's business base is dominated by small and medium-sized enterprises with limited capital and few specialist staff. Lean management, digital technologies and resource optimisation are usually studied apart, which leaves managers without a clear view of how the three combine. This review asks how they jointly shape sustainable industrial performance and what that implies for Australia's manufacturing sector. A systematic integrative design was used to synthesise 30 peer-reviewed journal articles published between 2020 and 2025, anchored by a review of additive manufacturing in Australian small and medium-sized enterprises and a national survey of 352 such enterprises on circular economy adoption. Ten of the articles draw on Australian or Australasian evidence. Three findings stand out. First, lean practice tends to improve operational results before environmental and social ones, and its sustainability gains depend on complementary practices rather than on lean tools alone. Second, digital technologies act chiefly as amplifiers: they make flows, defects and energy use visible and allow scenarios to be tested, but they rarely target resource efficiency explicitly. Third, in Australia the binding constraints are economic and institutional, including budget limits, weak market incentives, low domestic use of recycled material and fragmented policy, rather than a shortage of techniques. The paper proposes a multi-scale model linking process, enterprise and precinct levels, together with a four-stage adoption sequence for smaller manufacturers, and identifies priorities for research on resource-productive manufacturing in Australia.

1 Introduction

Manufacturing in Australia operates far from the largest global markets and within an economy whose business base is dominated by small and medium-sized enterprises (SMEs). These enterprises account for 97.4% of all Australian businesses and about a third of economic activity by revenue (Chakraborty et al., 2023). Unlike large companies, they often lack the resources to finance new equipment or absorb the risk of failed projects (Bianchini et al., 2024). At the same time, climate change and sustainable development goals are pushing manufacturers to understand and reduce their environmental impact alongside their economic results (Saari et al., 2024).

Three bodies of practice speak to this challenge. Lean management, with its emphasis on flow, waste elimination and continuous improvement, has established itself as the dominant improvement paradigm in manufacturing (Henao and Sarache, 2023). Digital technologies associated with Industry 4.0, including connected sensors, manufacturing execution systems, digital twins, artificial intelligence and additive manufacturing, promise greater visibility and flexibility. Resource optimisation, which spans energy efficiency, material efficiency and circular economy practice, addresses the physical inputs and outputs of production directly. Each has a substantial literature, but

the three are usually examined separately, and the studies that do combine them mostly come from outside Australia.

The separation matters because the three approaches interact. Lean practice can support environmental gains, yet the resources it demands may also come at the expense of environmental and social performance (Henao and Sarache, 2023). Digital systems can make energy and scrap visible, yet most artificial intelligence applications in manufacturing are not designed with resource efficiency as their stated purpose (Waltersmann et al., 2021). Circular practices often depend less on technique than on relationships between firms and on the incentives created by policy (Halog et al., 2021; King et al., 2020). Treating any one approach in isolation therefore risks overstating what it can achieve.

Australian evidence on these questions is thin and scattered across disciplines, from operations management and energy economics to waste policy and materials engineering. This review draws it together with the international literature to build an integrated account of how lean management, digital technologies and resource optimisation contribute to sustainable industrial performance, defined here as the joint improvement of economic, environmental and social outcomes. The contribution is threefold: an evidence-based synthesis of how the approaches combine; an analysis of the Australian conditions that shape their adoption; and a multi-scale model with an adoption sequence suited to smaller manufacturers.

After the research questions and the method are set out, the evidence on each approach is synthesised in turn, ending with the Australian setting. The discussion interprets the findings, proposes priorities for further study and records limitations, and the conclusion closes the paper.

2 Aim, objectives and research questions

The central aim is to show how lean management, digital technologies and resource optimisation together contribute to sustainable industrial performance and to translate that explanation into guidance for Australia's manufacturing sector. Four objectives follow from this aim: (1) to assess recent evidence on the relationship between lean practice and economic, environmental and social performance; (2) to examine how digital technologies complement lean practice and support energy and material efficiency; (3) to identify the economic, institutional and organisational conditions that shape adoption in Australian manufacturing; and (4) to develop an integrated model and adoption sequence that managers and policymakers can use.

Three research questions guide the synthesis. RQ1 asks what the 2020 to 2025 evidence shows about the effects of lean management, including its green and Six Sigma variants, on the three dimensions of sustainable performance. RQ2 asks how digital technologies interact with lean practice and contribute to resource and energy optimisation in manufacturing. RQ3 asks which conditions in Australia's manufacturing sector enable or constrain the combined use of these approaches, and what integrated model suits those conditions. RQ1 is addressed in the section on lean management, RQ2 in the section on digital technologies and RQ3 in the section on the Australian context, before the threads are brought together in the discussion.

3 Review methodology

A systematic integrative design was adopted because it allows quantitative, qualitative, design-oriented and review studies to be synthesised within one conceptual account. This breadth was

needed because the questions span operations management, information systems, energy economics and circular economy research, each with its own methods and standards of evidence.

Searches of a large scholarly metadata index were run in November 2026 using combinations of three term groups: lean terms ("lean manufacturing", "lean six sigma", "green lean", "value stream mapping"); digital terms ("Industry 4.0", "digital twin", "manufacturing execution system", "artificial intelligence", "additive manufacturing"); and resource terms ("energy efficiency", "energy productivity", "resource efficiency", "circular economy", "industrial symbiosis", "waste"). A separate stream combined these with "Australia" and "Australian" to locate national evidence, and titles were screened for explicit Australian or Australasian settings.

To be included, a study had to have appeared in a peer-reviewed journal from 2020 to 2025, be written in English, address manufacturing or closely related industrial production, and report empirical findings, a systematic review or a validated framework relevant to at least one research question. Conference papers, editorials, retracted articles and studies outside the publication window were excluded. Each candidate's metadata were checked against its registered digital object identifier, and articles without an accessible abstract or summary were set aside because their claims could not be verified.

Two anchor studies were selected before screening because they define the Australian starting point: a review of additive manufacturing techniques and pathways for Australian SMEs (Rooney et al., 2023) and a survey of 352 Australian SMEs on the barriers and enablers of circular economy adoption (Chakraborty et al., 2023). The remaining 28 articles were chosen for relevance, methodological transparency and coverage of the three approaches. The final corpus contains nine quantitative studies, two mixed-method studies, ten case, interview or design studies and nine reviews or conceptual frameworks.

Each article was coded for setting, method, the approaches examined, the performance dimensions measured, the mechanisms proposed and the contextual conditions reported. Codes were compared across studies to identify convergent findings, contradictions and gaps, and claims made in this paper were checked against the source abstracts and, where available, full texts. No new primary data were collected, and no figures have been estimated beyond those reported by the cited authors.

4 Lean management and the triple bottom line

Whether lean practice advances sustainability or merely efficiency is a question with a conditional answer. The most direct test in the corpus comes from 133 Colombian metalworking firms, where structural equation models supported a cumulative "sand-cone" sequence: lean improved operational performance first, then environmental performance, and then social performance (Henao and Sarache, 2023). The same study found partial evidence of trade-offs at the expense of social outcomes, which suggests that the resources lean consumes can crowd out attention to people if managers are not deliberate.

Evidence from smaller firms in developing economies points in a similar direction while adding qualifications. A survey of 166 Ghanaian manufacturing SMEs found that lean operations had positive effects on eco-product innovativeness and on social, green and business performance, but that eco-product innovativeness did not itself improve business performance (Afum et al., 2021). Among 259 Yemeni manufacturing SMEs, lean practices raised sustainable performance indirectly through corporate social responsibility, and this indirect effect weakened as competitive intensity rose (Al-

Swidi et al., 2024). The pattern suggests that intense competition can narrow the sustainability dividend of lean.

A second qualification concerns complementarity. In a study of 178 Chinese manufacturers, individual lean bundles, covering just-in-time production, quality management and human resource practices, did not always improve sustainable performance on their own, whereas their combination with servitisation did (Hao et al., 2021). In Pakistani manufacturing SMEs, green manufacturing and circular economy practices partially mediated the relationship between Lean Six Sigma and operational performance (Fayyaz et al., 2025). Both studies imply that lean is better understood as a platform onto which environmental and service practices are added than as a self-sufficient route to sustainability.

The green extension of Lean Six Sigma formalises this idea. A framework built on the define, measure, analyse, improve and control cycle integrates green, lean and Six Sigma elements through enablers, a combined toolset and implementation methods, and argues that dedicated indices are needed to measure the sustainability effects of projects (Kaswan and Rathi, 2020). A review of 157 articles on lean and green practice in SMEs found few empirical studies that assess effects on supply chain sustainability across all three dimensions of the triple bottom line, and no workable model designed for smaller firms (Kosasih et al., 2023). The tools exist, in other words, but their effects on smaller manufacturers remain under-measured.

In this corpus, Australian evidence on lean comes mainly from a comparative case study of Lean Six Sigma in 12 Australian and New Zealand organisations and four in the United States. Definitions of a Lean Six Sigma project differed markedly between the regions, while practices for selecting, initiating and executing projects were similar. None of the Australasian organisations had the formal reporting structures common in the United States, yet implementation success was unaffected (Perera Halnetti et al., 2024). For Australian managers, this finding is encouraging: the benefits of structured improvement do not appear to depend on heavy programme bureaucracy, which smaller firms could not sustain.

Taken together, the studies support three answers to RQ1. Lean practice reliably improves operational performance and can support environmental and social gains. Those wider gains tend to follow operational ones and depend on complementary green, circular, service or social responsibility practices. And the effects are moderated by context, especially competitive intensity and firm size, which makes measurement of all three dimensions, rather than cost alone, a precondition for knowing whether lean is serving sustainability.

5 Digital technologies as amplifiers of Lean and resource efficiency

Reviews of lean and Industry 4.0 agree that combining them can raise productivity and flexibility. A review of studies on lean tools and digital technologies found that integration improves productivity, speed and accuracy while retaining lean's emphasis on people and continuous improvement (Singh and Singh, 2024). A systematic review of 92 articles proposed a lean automation framework and noted that many organisations still struggle to integrate the two approaches in practice despite their documented benefits (Saraswat et al., 2025). The difficulty lies less in the technology than in the sequence and design of its introduction.

Case evidence clarifies that sequence. In a large manufacturer that introduced autonomous guided vehicles and the internet of things into lean operations, a plan based on socio-technical design

proceeded through three phases: design, integration and continuous improvement. Success depended on managing the interplay of social factors such as people and culture, technical factors such as infrastructure, and operational routines (Vlachos et al., 2023). In a cutlery SME, a combined lean and digital project produced a 27.6% reduction in throughput time and a 36.5% increase in productivity. The authors attributed the result to three conditions: top management commitment, knowledge of both lean and digitalisation, and a very low initial value-added ratio (Dinis-Carvalho et al., 2023). The third condition is a reminder that large gains are easiest where waste is greatest.

Digital tools also support the human side of lean. A truck cooler manufacturer that combined the Six Sigma improvement cycle with digitally supported value stream mapping redesigned a picking workstation around its operators. Yield rose from 98% to 100%, and direct savings of EUR 3,180 came mainly from freed floor space (Wang et al., 2022). The modest financial figure is as instructive as the quality gain: many digitally supported lean projects deliver incremental value, which smaller firms must weigh carefully against implementation costs.

For smaller manufacturers, the data infrastructure itself is often the first hurdle. A study of manufacturing execution system implementation in a manufacturing SME presented a key performance indicator framework built on the system's data. It argued that moving from large volumes of raw data to selected, decision-relevant data supported efficiency, cost tracking, the balancing of workloads, better use of resources and greater operator engagement (Bianchini et al., 2024). The same study noted that budget constraints and the difficulty of measuring benefits early in a project deter SMEs from such investments.

The contribution of digital technologies to resource optimisation is real but less direct than often claimed. A review of 70 studies on artificial intelligence in manufacturing found that only a minority addressed resource efficiency as an explicit objective. The relevant uses clustered around maintenance prediction, planning of production, detection of faults and quality, and energy management, and the review called for sustainability to be considered in the design of artificial intelligence itself (Waltersmann et al., 2021). Digital twins show how scenario testing can reduce waste: in two manufacturing cases, simulations showed that adding quality control at every assembly station would raise efficiency and significantly cut raw material consumption and waste (Resman et al., 2025).

Energy is the resource most often targeted. A tertiary review of systematic reviews published between 2016 and 2022 grouped research on manufacturing energy efficiency into six categories: diagnosis, metering, optimisation, technology, strategic paradigms, and drivers and barriers. It organised them under three forms of knowledge: process, technical and leadership (Ibn Batouta et al., 2023). The inclusion of leadership knowledge matters: metering and optimisation tools are unlikely to produce savings unless someone is accountable for acting on the data. Among manufacturing SMEs in the Finnish region of Ostrobothnia, readiness for energy optimisation and Industry 4.0 varied markedly with firm size, reflecting differences in resources, technological capability and willingness to act. Regulatory complexity and weak market incentives slowed progress further (Paalosmaa, 2025).

Survey evidence links digital adoption to sustainable performance through intermediate practices rather than directly. In the Pakistani food manufacturing sector, adoption of Industry 4.0 technologies improved sustainable performance through green supply chain collaboration, circular economy practices and technological readiness, and environmental dynamism strengthened these relationships (Farrukh Shahzad et al., 2025). A Delphi and best-worst prioritisation study of manu-

facturing sustainability practices ranked circular economy practices first, cleaner production second and Industry 4.0 third. Supply chain traceability and information, reuse and recycling infrastructure, and a clean natural environment emerged as the leading practices (Gupta et al., 2021).

The answer to RQ2 is therefore that digital technologies function mainly as amplifiers and enablers. They make waste, defects and energy use visible, support decisions and allow changes to be tested before resources are committed. Their sustainability value depends on being directed at lean and resource objectives, on data that managers actually use, and on intermediate practices such as supply chain collaboration and circular design. Technology deployed without these links tends to raise output without necessarily reducing resource intensity.

6 Resource optimisation and circularity in the Australian context

Australia's energy productivity record shows why resource optimisation cannot be left to technical efficiency alone. An analysis of energy productivity across Australian sub-industries between 2003 and 2015 decomposed change into technical efficiency, technological change and shifts in factor ratios. Technical efficiency contributed positively, but declining technological change was the main driver of falling energy productivity in eight sub-industries. Falling capital-energy and labour-energy ratios dominated the decline in ten sub-industries between 2007 and 2015 (Doojav and Kalirajan, 2020). Operational housekeeping, in other words, appears not to have been the main problem; the shortfall lay in investment in better production technology and in how capital and labour were combined with energy.

Circular economy activity is more advanced in heavy industry than in mainstream manufacturing. A systematic review of Australian practice found eco-industrial parks in metals and metallurgy and identified mining-linked precincts at Kwinana in Western Australia and Gladstone in Queensland as leaders. It also listed barriers including short-sighted views of supply chain opportunities, technological constraints, poor policy coordination, the pandemic recession and weak incentives for behavioural change (Halog et al., 2021). Kwinana, where more than 150 exchanges of products and by-products have been documented, has been proposed as a model in which skilled workforce, support industry and governance dimensions operate alongside material exchange. Its water cases include both a failed aquifer recharge project and successful sharing of process water among co-located firms (Oughton et al., 2021).

Smaller manufacturers need different mechanisms from those of heavy-industry precincts. A study of the ASPIRE matchmaking network for SMEs found that firm attributes, rather than network structure, drove contact for industrial symbiosis. Recyclers were central senders and receivers of contact, and facilitator contact, prior personal relationships and interest in using recycled material raised the likelihood of engagement, whereas geographic proximity did not (King et al., 2020). The finding suggests that, for SMEs, digital matchmaking supported by active facilitators can substitute for the co-location on which traditional symbiosis relies.

Market and policy signals remain weak. The survey of Australian SMEs identified budget constraints, low customer awareness and the absence of clearly defined business processes as major barriers to circular adoption. It also found that barriers and enablers varied by industry, location and respondent role, and called for consistent policies tailored to sectors and locations (Chakraborty et al., 2023). Plastics illustrate the scale of the gap: Australia consumed about 3.5 million tonnes of plastics in 2018 to 2019, recovered only 11.5%, and local use of recycled material stood at only about 10% across sectors (Hossain et al., 2022). Interviews with 20 representatives of circular intermediary organisa-

tions found that national policy had concentrated on recycling and waste management, and that intermediaries held a more nuanced view of the transition than the green growth narrative of policy and industry media (Melles, 2023).

A case study of the Australian cheese industry shows how incentives operate at firm level. Interviews with 42 firms, representing 31% of the industry, found that profit maximisation, environmental protection and government regulation were the main motivators for managing whey, the principal by-product, but with considerable variation between firms. Regulation alone did not move firms up the food waste hierarchy; one firm facing non-compliance penalties of AU$160,000 shifted only sideways within the disposal level. On the study's sample, diverting all whey currently classed as waste could meet 41% of the industry's reduction target (Hetherington et al., 2025). Resource optimisation here depends on markets for by-products and on combined pressures, not on production technique.

Technology can still open new options for smaller firms. Rooney et al. (2023) described vat polymerisation, environmentally friendly and multi-material techniques used in Australian SMEs. They argued that additive processes allow local firms to tailor products to diverse customers with shorter lead times, and a jewellery case showed how such processes were built into production to reduce lead time and cost. These capabilities suit a manufacturing base that competes on customisation and speed rather than scale. Maturity tools can help firms decide what to do next: a circular economy matrix combining five maturity levels with seven value chain phases was piloted in nine manufacturers in Finland, Italy, Germany and Ireland. None of the firms remained at the linear level, and more than 40 circular actions were identified (Saari et al., 2024).

Table 1 summarises the Australian evidence. Read together with the two preceding sections, it answers RQ3: the techniques available to Australian manufacturers are broadly the same as those used elsewhere, but adoption is constrained by firm size and capital, by weak markets for secondary materials, by fragmented and recycling-focused policy, and by low investment in production technology. Relationships between firms, through precincts, networks and intermediaries, emerge as an enabling condition that has no close parallel in the lean and digital literatures.

Table 1. Australian and Australasian evidence on lean, digital and resource practice in manufacturing.

Study	Setting and method	Principal finding	Implication
Rooney et al. (2023)	Review; additive manufacturing in SMEs; jewellery case	Additive processes cut lead time and cost and allow tailored products	Customisation and speed suit small-scale manufacturers
Chakraborty et al. (2023)	Survey of 352 SMEs	Budget limits, low customer awareness and undefined processes impede circular adoption	Sector- and location-specific policy support is needed
Halog et al. (2021)	Systematic review of circular economy	Progress led by metals and mining precincts; policy coordination and incentives weak	Extend circular practice beyond heavy industry
Oughton et al. (2021)	Case study, Kwinana Industrial Area	Over 150 exchanges; workforce, support industry and governance shape symbiosis	Symbiosis rests on institutions as well as materials
King et al. (2020)	Network analysis of SME matchmaking	Firm attributes and facilitators drive contact; proximity not significant	Facilitated networks can substitute for co-location

Study	Setting and method	Principal finding	Implication
Perera Halnetti et al. (2024)	12 Australasian and 4 US cases	Similar project practices; no formal reporting structures, yet success unaffected	Lean Six Sigma can work without heavy bureaucracy
Hetherington et al. (2025)	Interviews with 42 cheese manufacturers	Profit, environment and regulation motivate; penalties alone insufficient	Combine regulation with by-product markets
Doojav and Kalirajan (2020)	Decomposition of energy productivity, 2003–2015	Weak technological change and falling factor ratios drove declines	Invest in production technology, not only housekeeping
Melles (2023)	Interviews with 20 circular intermediaries	Policy focused on recycling and waste; transition more complex than green growth claims	Broaden policy beyond recycling
Hossain et al. (2022)	Systematic review of plastic waste data	11.5% recovery; local recycled material use about 10%	Create demand for secondary materials

6.1 An integrated multi-Scale model

These findings support a model in which the three approaches operate across three scales (Figure 1). At the process scale, lean methods stabilise flow and expose waste, digital tools measure and simulate, and resource practices target energy, scrap and water at individual operations. At the enterprise scale, improvement systems, execution and performance data, and circular design and maturity planning are coordinated through management routines and measures covering all three sustainability dimensions. Across precincts and networks, firms exchange by-products, water and energy through co-location or facilitated matchmaking, supported by shared skills, support industries and governance. Table 2 sets out the lean, digital and resource levers and the indicative measures at each scale, together with the conditions that cut across them.

Table 2. Levers and measures across the three scales of the integrated model.

Scale	Lean lever	Digital lever	Resource lever	Indicative measures
Process	Standard work, flow, mistake-proofing, value stream mapping	Sensors, metering, execution system data, simulation	Scrap, energy and water reduction at operations	Throughput time, yield, energy per unit, scrap rate
Enterprise	Improvement routines; green Lean Six Sigma projects	Indicator frameworks; analytics; digital twins	Circular design; maturity planning; additive processes	Triple bottom line scorecard; value-added ratio; recycled content
Precinct and network	Shared improvement capability; supplier development	Matchmaking platforms; traceability data	By-product, water and energy exchange	Exchanges completed; tonnes diverted; shared infrastructure use
Cross-scale conditions	Management commitment and skills	Technological readiness and data use	Markets, incentives and policy coordination	Investment rates; policy coverage; secondary material prices

The model makes two claims. First, gains at one scale are limited unless the adjacent scale is ready: process data are of little use without enterprise routines to act on them, and by-product exchange requires stable, well-characterised processes in the participating firms. Second, policy and market

conditions act mainly at the enterprise and precinct scales, which is where Australian constraints are most acute.

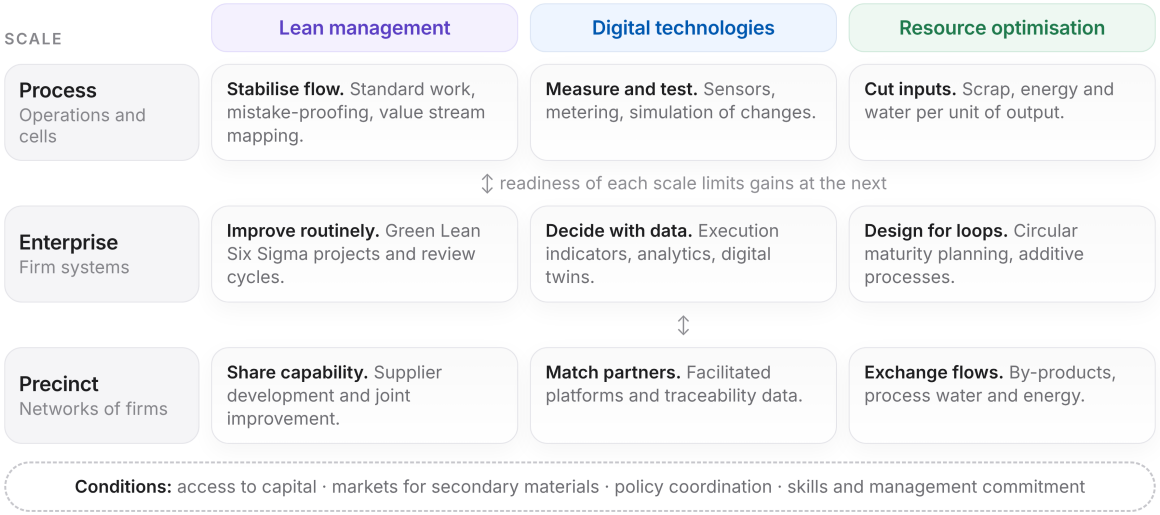


Figure 1. Multi-scale model linking lean management, digital technologies and resource optimisation in manufacturing.

For smaller manufacturers, the model implies an adoption sequence (Figure 2). Stage 1, stabilise, establishes standard work, visual management and basic improvement routines, which, as the Australasian Lean Six Sigma cases suggest, need not depend on complex programme structures. Stage 2, measure, introduces selective digital data capture, such as execution system indicators and energy metering, focused on the measures that matter. Stage 3, optimise, uses analytics, simulation or additive processes to reduce scrap, energy and lead time, testing changes virtually where possible. The final stage, connect, extends attention beyond the factory to by-product markets, symbiosis networks and circular design. The stages overlap in practice, but the sequence reflects the evidence that sustainability gains build on operational stability and that digital investment pays off when processes are already understood.

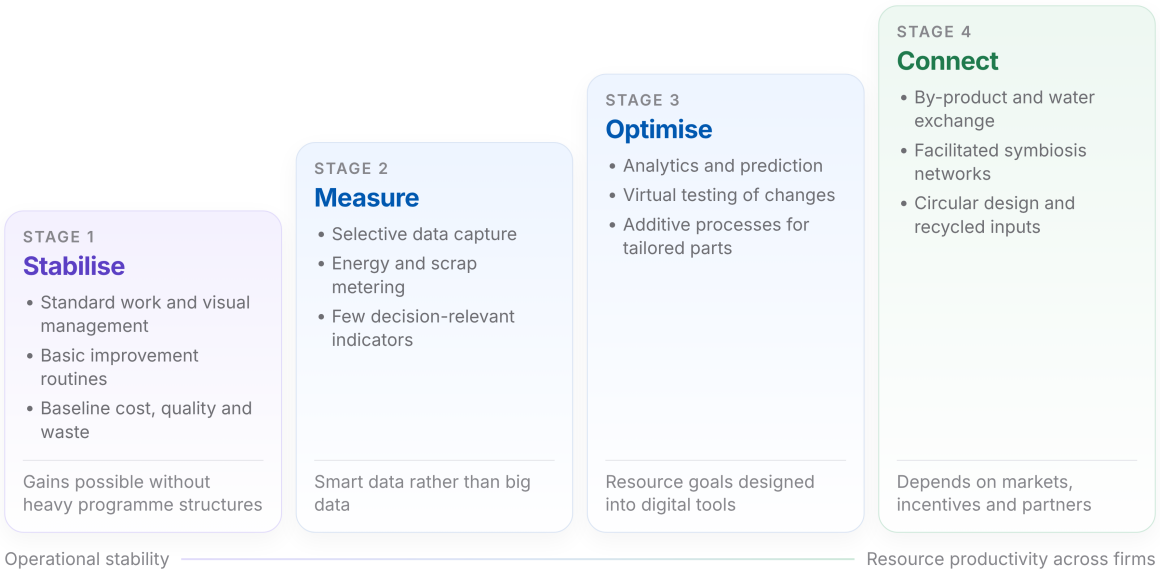


Figure 2. Four-stage adoption sequence for resource-productive manufacturing in smaller firms.

7 Discussion, research agenda and limitations

Two common assumptions are challenged by this synthesis. The first is that lean and sustainability are naturally aligned. The evidence supports alignment, but only partially and in sequence: operational gains come first, environmental and social gains depend on complementary practices, and competitive pressure can erode the wider benefits (Al-Swidi et al., 2024; Henao and Sarache, 2023). The second is that digital technology will deliver resource efficiency as a by-product of automation. The literature shows instead that resource efficiency must be designed into digital applications and linked to management routines (Ibn Batouta et al., 2023; Waltersmann et al., 2021).

For Australia, the analysis shifts attention from technique to conditions. Australian firms appear to implement structured improvement effectively without elaborate programme structures (Perera Halnetti et al., 2024), and some precincts are internationally recognised for industrial symbiosis (Oughton et al., 2021). The weaker links are investment in production technology, markets for secondary materials and policies that look beyond recycling (Doojav and Kalirajan, 2020; Hossain et al., 2022; Melles, 2023). This diagnosis implies that support programmes should combine improvement capability with access to capital, facilitated networks and demand for recycled inputs, rather than funding technology alone.

Theoretically, the review extends complementarity arguments in operations management (Hao et al., 2021) to the relationship among lean, digital and resource practices, and adds a spatial dimension through the precinct scale. It also connects the operations literature with research on industrial symbiosis networks, where social relations and facilitation shape outcomes (King et al., 2020). The multi-scale model offers a way to locate studies that are usually read in isolation and to specify where interactions between scales should be tested.

The practical implications differ by audience. Owners and managers of smaller manufacturers can start with low-cost stabilisation and a short list of measures that include energy, scrap and safety as well as cost, so that the wider effects of improvement are visible from the outset. Engineering staff should treat digital projects as experiments with stated resource targets, using simulation or pilot

cells before committing capital, and should expect the largest gains where flow is poorest. Industry associations and precinct managers can extend the facilitation role shown in the ASPIRE network by brokering by-product exchanges and sharing improvement expertise across firms. Governments can complement these efforts by linking grants for equipment to demonstrated improvement capability, by creating demand for recycled inputs through procurement and standards, and by coordinating circular economy policy across jurisdictions so that firms face consistent signals.

Five priorities for research follow. First, Australian studies should measure lean and digital effects on all three dimensions of sustainable performance in the same firms, ideally over several years. Second, the adoption sequence in Figure 2 should be tested, for example by comparing firms that digitalise before stabilising processes with those that follow the opposite order. Third, research should examine how artificial intelligence and digital twin projects can be designed with explicit energy and material objectives in smaller manufacturers. Fourth, the conditions under which facilitated networks substitute for co-location deserve comparative study across Australian regions. Fifth, the interaction of policy instruments, including regulation, penalties and market creation for secondary materials, with firm-level improvement capability remains poorly understood.

The review has limitations. The corpus was restricted to 30 journal articles, and some relevant work in reports, theses and conference proceedings was excluded. Australian manufacturing evidence is limited, so several conclusions draw on studies from Colombia, China, Ghana, Yemen, Pakistan and Finland, whose conditions differ from Australia's. Several studies rely on self-reported survey data or single cases. Full texts were not accessible for every article, so some claims rest on abstracts and summaries, and screening and coding were carried out by a single reviewer. The model and adoption sequence are propositions derived from the synthesis and require empirical testing.

8 Conclusion

This review sought to establish how lean practice, digitalisation and the careful use of energy and materials combine to improve the economic, environmental and social results of Australian manufacturers. The evidence indicates that lean provides an operational foundation whose environmental and social benefits depend on complementary practices. Digital technologies amplify improvement and make resources visible but rarely target resource efficiency without deliberate design. Resource optimisation in Australia is constrained less by technique than by capital, markets, policy and the small scale of most firms.

The proposed multi-scale model links process, enterprise and precinct levels, and the four-stage sequence of stabilising, measuring, optimising and connecting offers smaller manufacturers a practical path. For managers, the main implication is to measure sustainability outcomes alongside cost and to direct digital investment at specific waste and energy problems. For policymakers, it is to pair improvement support with access to capital, facilitated networks and demand for recycled materials. Progress on all three fronts would allow Australian manufacturing to become more productive and less resource-intensive at the same time.

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