

Environmental Digital Capability in Mandated Industry 4.0 Implementation at HAL and BEL

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Abstract

Industrial digitalisation is often presented as an enabler of sustainable manufacturing, but implementation maturity is not equivalent to measured environmental improvement. This study examines environmental digital capability under a common government-mandated Industry 4.0 and Quality Assurance 4.0 assessment framework, using monthly administrative records from Hindustan Aeronautics Limited (HAL) and Bharat Electronics Limited (BEL) for May–October 2025. An Environmental Digitalisation Index (EDI) is calculated as the unweighted mean of three environmental implementation parameters: waste-reduction automation, material-utilisation monitoring and environmental-compliance digitalisation. To avoid overlap with the environmental parameters embedded in the original production maturity score, a sensitivity comparator is calculated from the five non-environmental Industry 4.0 categories (P1–P5), with their weights renormalised to 100%. Environmental implementation trajectories were broadly similar to the adjusted production index, although the mean adjusted PDI–EDI gap was 6.3 index points for HAL and 5.1 for BEL. EDI exceeded the harmonised two-item Digital Traceability Index (DTI) in five of six months in each organisation. Reported annualised man-hour effects are examined descriptively through exploratory lagged correlations, which cannot establish temporal precedence or causality. The study contributes a sub-parameter-level account of environmental digital capability development and demonstrates why implementation indices should be distinguished from measured environmental outcomes.

1 Introduction

Manufacturing digitalisation is frequently associated with opportunities to improve resource efficiency, process visibility and environmental management. Sensors and connected systems can make production conditions more observable; analytics may support process adjustment; and digital records can preserve information about materials and components across production and service. At the same time, digital technologies have environmental footprints of their own, and efficiency gains do not automatically translate into lower total environmental burdens. The relationship between Industry 4.0 and sustainability is therefore conditional on the functions implemented, the organisational setting and the outcomes measured [1–3].

An important distinction is between digital implementation and sustainability performance. An assessment score may document that a digital function has been implemented, but it does not by itself establish a reduction in energy use, material consumption, waste or emissions. This distinction matters in empirical work because studies that combine adoption and performance into broad composite measures can obscure which functions are present and whether environmental outcomes have actually changed [1, 2].

A further issue concerns the level of detail at which environmental digitalisation is examined. Process-oriented functions such as waste-reduction automation, material-utilisation monitoring and environmental-compliance digitalisation are different from traceability functions that preserve information about components, lots and changes. The former are more directly associated with operational visibility and in-process management; the latter may support product stewardship and downstream recovery. These functions may develop at different rates, yet a single digital maturity score can conceal such differences. The natural-resource-based view (NRBV) provides a useful interpretive distinction between pollution prevention and product stewardship [4].

Mandated digitalisation offers a setting in which organisations implement under a common assessment framework. Institutional theory suggests that formal requirements can shape visible organisational practices, although common reporting requirements do not eliminate differences in operational routines or implementation context [5]. The present study examines two Indian defence manufacturers: Hindustan Aeronautics Limited (HAL) and Bharat Electronics Limited (BEL), using six monthly assessment cycles from May to October 2025. The cases operate in different manufacturing subsectors, but their records were prepared under the same broad Industry 4.0 and Quality Assurance 4.0 assessment framework.

The study addresses three research questions: (1) How did environmental digitalisation progress relative to production digitalisation in HAL and BEL? (2) How did environmental implementation parameters compare with traceability parameters over the observation period? (3) What exploratory patterns are visible between environmental digitalisation and reported man-hour savings when contemporaneous and lagged associations are examined?

The study makes three contributions. First, it provides a longitudinal, sub-parameter-level description of environmental digital implementation using verified administrative records rather than perception measures. Second, it separates environmental process parameters from a harmonised traceability measure, making implementation asymmetries visible. Third, it distinguishes implementation completion from reported operational productivity and from measured environmental performance. The study does not claim to estimate the causal effect of the mandate or to demonstrate reductions in environmental impacts.

2 Literature review and theoretical framing

2.1 Industry 4.0 and sustainability

Industry 4.0 encompasses connected production technologies, data acquisition, analytics and automation. These technologies can support sustainability when they improve process information, reduce avoidable losses or enable lifecycle coordination. Reviews of digitalisation in manufacturing, however, also identify environmental burdens associated with hardware production, energy use and end-of-life treatment [1–3]. Consequently, the sustainability implications of digitalisation should not be inferred from adoption alone.

For the present study, the relevant distinction is between the presence of an environmental digital function and the environmental result it may enable. A completion ratio is an implementation indicator. It may indicate that an organisation has established a system or automated a process, but it cannot show whether that system is used effectively or whether environmental performance improved. The analysis therefore focuses on capability development and treats the reported man-hour figures as operational productivity information, not as environmental outcomes.

2.2 Natural-resource-based view

Hart's NRBV identifies pollution prevention, product stewardship and sustainable development as strategic responses to environmental constraints [4]. Pollution prevention concerns reducing environmental burden through process improvement, while product stewardship extends attention across the product lifecycle and requires coordination beyond the immediate production process. The distinction is useful for interpreting the different functions captured in the assessment records.

In this study, waste-reduction automation, material-utilisation monitoring and environmental-compliance digitalisation are grouped as environmental process-oriented parameters. Component-level traceability and end-to-end lot tracking are treated as a separate traceability domain. This mapping is an analytical classification based on the primary function described in the assessment instrument; it is not a claim that the technologies have only one sustainability function. Nor does the NRBV imply that monitoring must causally precede traceability in every organisation. The framework is used to interpret the observed implementation pattern, not to assert a mechanism that the data cannot identify.

2.3 Institutional context and mandated implementation

Institutional theory explains how coercive, mimetic and normative pressures can influence organisational structures and practices [5]. A government-mandated assessment framework is consistent with coercive institutional pressure because it specifies parameters against which implementation is reported. Yet a common reporting framework does not make organisations identical: manufacturing technologies, local routines, available resources and reporting practices may still differ.

The two cases allow a bounded comparison of implementation trajectories under a shared assessment environment. Because there is no non-mandated comparison group and only two organisations are observed, the design cannot isolate a mandate effect. The institutional perspective is therefore used to contextualise the cases and to develop cautious implications about the visibility of explicitly assessed environmental functions.

2.4 Analytical expectations

Rather than treating the small, repeated monthly series as a basis for confirmatory hypothesis testing, the analysis uses three descriptive expectations aligned with the research questions: environmental parameters may progress alongside production digitalisation; process-oriented environmental parameters may not follow the same trajectory as traceability parameters; and the association between implementation and reported productivity may vary across cases. These expectations guide interpretation but are not treated as statistically confirmed causal hypotheses.

3 Materials and methods

3.1 Research design and cases

The study uses a comparative longitudinal case design involving HAL and BEL. The observation window comprises six consecutive monthly assessment cycles from May through October 2025, yielding 12 organisation-month records. The cases were selected purposively because the relevant monthly assessment records were available for both organisations and because they represent different manufacturing contexts: aerospace/aviation and defence electronics.

The common assessment framework provides a shared reporting context, not a controlled experiment. The two organisations differ in process mix, production scale and the number and description of sub-parameters. Accordingly, comparisons are made at the level of explicitly harmonised measures, and conclusions are limited to the two cases and observation window.

Table 1
Case and measurement comparability.

Case	Manufacturing context	Observation window	Reporting context	EDI components	Common DTI components	Comparability boundary
HAL	Aerospace and aviation manufacturing	May–October 2025; six monthly forms	Same broad I4.0/QA4.0 assessment framework	Waste-reduction automation; material-utilisation monitoring; environmental-compliance digitalisation	Component-level traceability; end-to-end lot tracking	Different production mix and item denominators; October reported completion can exceed the committed baseline.
BEL	Defence electronics manufacturing	May–October 2025; six monthly forms	Same broad I4.0/QA4.0 assessment framework	Waste-reduction automation; material-utilisation monitoring; environmental-compliance digitalisation	Component-level traceability; end-to-end lot tracking	Different production mix and item denominators; QA4.0 completion remains below 100% in October.
<i>Note: The common framework supports a bounded comparison of selected parameters; it does not make the organisations or their full assessment instruments equivalent.</i>						

3.2 Data sources and verification

The data were extracted from the organisations’ monthly Industry 4.0 and Quality Assurance 4.0 assessment records and maintained in structured extraction workbooks with source-audit information. The workbooks record sub-parameter completion ratios and Section A summary measures, including reported cost savings and annualised man-hour effects. The source records were checked through the extraction audit trail and arithmetic consistency checks documented in the workbooks.

The analysis uses the six months for which the HAL and BEL records were treated as comparable for the present study. HAL’s reported Industry 4.0 completion count exceeded the baseline in the later months; such values were retained in the source records rather than capped, because they reflect reported completion beyond the stated baseline. The present environmental index is based on sub-parameter completion ratios and remains on a 0–100 scale.

The unit of analysis is the organisation-month. No individual-level records, employee responses or personal data are analysed. The manuscript reports only aggregated organisational indicators. The case organisations’ written permission for publication is stated by the authors; the original administrative records remain subject to applicable disclosure restrictions.

3.3 Measures and index construction

Environmental Digitalisation Index (EDI). EDI is the unweighted arithmetic mean of the completion ratios for three environmental implementation parameters: waste-reduction automation, material-utilisation monitoring

and environmental-compliance digitalisation. For organisation i in month t , $EDI_{it} = 100 \times (x1_{it} + x2_{it} + x3_{it})/3$, where each x is the reported completion ratio expressed between 0 and 1. The index represents reported implementation completion, not an environmental outcome.

Digital Traceability Index (DTI). To improve cross-case comparability, DTI is calculated from the two traceability functions available in both records: component-level traceability and end-to-end lot tracking. $DTI_{it} = 100 \times (z1_{it} + z2_{it})/2$, where $z1$ and $z2$ are the respective completion ratios. Other traceability-related parameters present in one organisation's assessment instrument were not included in the cross-case DTI. This harmonisation improves comparability but narrows the construct to the two common items.

Production Digitalisation Index (PDI). The original PDI is the organisation-level Industry 4.0 composite maturity score reported in the verified analytical records. The original composite includes P6: Energy & Sustainability, which overlaps with the environmental parameters used to construct EDI. To avoid a part-whole comparison, the principal PDI-EDI comparison therefore uses a sensitivity comparator calculated from P1-P5 only, with the five category weights renormalised from 85% to 100%. This adjusted PDI is a study-specific sensitivity measure, not a validated scale or a replacement for the organisation-reported composite. The original PDI is retained only for transparency in Supplementary Material 1.

Reported resource-productivity outcomes. The monthly assessment forms report cost savings and manpower optimisation (MH/year) as organisational estimates. The extraction workbooks identify these as approximate values reported on each form; they do not establish whether successive monthly values are incremental, cumulative, or revised annualised estimates. Accordingly, the analysis treats them as reported monthly-form estimates and does not interpret their increase as a verified accumulation of realised savings. They are not direct measures of environmental performance.

Missingness and scope. The source extraction workbooks distinguish zero implementation from values that were not reported or could not be quantified. Only the selected common parameters with numeric monthly completion ratios enter the indices. The component definitions and monthly values used in the present analysis are reproduced in Supplementary Material 1.

Table 2
Operational definitions and interpretation of the index components.

Index	Parameter	Operational definition used	Interpretive boundary
EDI	Waste-reduction automation	Reported completion ratio for the corresponding environmental sub-parameter.	Implementation of a waste-related digital function; not tonnes of waste prevented or reduced.
EDI	Material-utilisation monitoring	Reported completion ratio for the corresponding material-use monitoring sub-parameter.	Implementation of monitoring capability; not measured material intensity or savings.
EDI	Environmental-compliance digitalisation	Reported completion ratio for the corresponding environmental-compliance sub-parameter.	Implementation of a digital compliance function; not proof of compliance performance or improved disclosure.
DTI	Component-level traceability	Reported completion ratio for the component-level traceability item common to both organisations.	Implementation of a selected traceability function; not proof of full lifecycle traceability.
DTI	End-to-end lot tracking	Reported completion ratio for the end-to-end lot tracking item common to both organisations.	Implementation of a selected traceability function; not proof of material recovery or circularity.
<i>Note: EDI and DTI are study-specific descriptive indices based on reported completion ratios.</i>			

3.4 Analytical procedure

The analysis proceeds in four steps. First, the original organisation-reported PDI is decomposed into its six weighted categories. Because P6: Energy & Sustainability overlaps with the environmental parameters used in EDI, a non-overlapping comparator is calculated from P1–P5, with their weights renormalised to 100%; the monthly gap is calculated as adjusted PDI minus EDI. Second, EDI and DTI trajectories are compared descriptively using monthly index values and within-case gaps. No inferential test is used because the data comprise repeated monthly observations from only two organisations, and the time points are not independent organisational units. Third, Pearson correlations are calculated between EDI at month t and the reported MH/year value on the form for month t , $t + 1$ and $t + 2$, separately for each organisation. Effective sample sizes are six, five and four pairs, respectively. These calculations are exploratory: the series are short and trend over time, and the underlying reporting convention does not establish that the values are independent monthly realisations. Nominal p -values are therefore not interpreted as confirmatory evidence or as evidence of benefit timing. Fourth, the monthly source values and index calculations are checked against the extraction workbooks. The selected series and calculation rules are supplied in Supplementary Material 1.

4 Results

4.1 Environmental digitalisation relative to production digitalisation

Table 3 presents the production and environmental digitalisation trajectories using the adjusted P1–P5 production comparator. The original organisation-reported PDI includes the P6 Energy & Sustainability

category, which overlaps with EDI; it is therefore not used for the principal comparison. The mean adjusted PDI–EDI gap was 6.3 index points for HAL and 5.1 for BEL. The monthly pattern was not uniform. HAL’s EDI was below the adjusted PDI in May and June, exceeded it slightly in July and August, and was below it again in September and October. BEL’s EDI was above the adjusted PDI in May, below it from June through September, and equal to it in October. These are descriptive differences between study-specific indices, not evidence of statistical parity or equivalence.

Table 3
Adjusted production and environmental digitalisation trajectories, May–October 2025.

Month	HAL adjusted PDI	HAL EDI	HAL gap	BEL adjusted PDI	BEL EDI	BEL gap
May-25	30.0	0.0	30.0	31.4	33.3	-2.0
Jun-25	38.5	34.2	4.3	44.2	33.3	10.9
Jul-25	58.5	59.0	-0.5	57.8	33.3	24.5
Aug-25	71.7	74.0	-2.3	64.8	63.9	0.9
Sep-25	88.0	83.3	4.7	79.5	83.3	-3.9
Oct-25	93.5	92.2	1.3	100.0	100.0	0.0
Mean gap			6.3			5.1
<i>Note: Adjusted PDI is calculated from P1–P5 after excluding the overlapping P6 Energy & Sustainability category and renormalising weights to 100%. Gap = adjusted PDI – EDI; positive values indicate adjusted PDI above EDI. The original organisation-reported PDI is provided in Supplementary Material 1.</i>						

4.2 Environmental implementation and traceability trajectories

Table 4 compares EDI with a harmonised DTI based only on component-level traceability and end-to-end lot tracking, the two traceability functions available in both organisations. EDI exceeded DTI in five of six months for HAL (the indices were equal at zero in May) and in five of six months for BEL; in September, BEL’s DTI was effectively equal to EDI after rounding. The mean EDI–DTI gap was 25.5 points for HAL and 14.6 for BEL. The gap was therefore larger in HAL over this observation window, while BEL’s traceability index approached its environmental index in the final two months. These are descriptive case patterns, not evidence of a universal capability sequence.

Table 4
Environmental digitalisation and harmonised traceability indices.

Month	HAL EDI	HAL DTI	HAL gap	BEL EDI	BEL DTI	BEL gap
May-25	0.0	0.0	0.0	33.3	5.5	27.8
Jun-25	34.2	17.6	16.6	33.3	5.5	27.8
Jul-25	59.0	23.0	36.0	33.3	21.1	12.2
Aug-25	74.0	23.0	51.0	63.9	49.5	14.4
Sep-25	83.3	53.8	29.4	83.3	83.4	≈ 0.0
Oct-25	92.2	72.5	19.7	100.0	94.5	5.5
Mean gap			25.5			14.6
<i>Note: DTI is the mean of component-level traceability and end-to-end lot tracking. Gaps are calculated from unrounded index values; displayed values may differ slightly due to rounding.</i>						

4.3 Exploratory associations with reported man-hour effects

The MH/year figures recorded on the monthly forms rose from 15,660 to 65,000 for HAL and from 9,500 to 37,000 for BEL between May and October 2025. The corresponding EDI–MH/year correlations are shown in Table 5. For HAL, the descriptive correlation increased from 0.943 concurrently to 0.994 at a two-month lag. For BEL, the concurrent correlation was 0.938 and declined to 0.744 at a two-month lag. These values are based on four to six pairs from short, trending series, and the source forms do not establish whether monthly values are independent realised savings or updated estimates. The correlations are therefore descriptive only; they do not establish that EDI precedes or causes productivity effects.

Table 5
Exploratory correlations between EDI at month t and reported annualised man-hour effects at the indicated month.

Organisation	Pairing	Pearson r	Nominal p	n
HAL	Concurrent	0.943	0.005	6
HAL	One month	0.972	0.006	5
HAL	Two months	0.994	0.006	4
BEL	Concurrent	0.938	0.006	6
BEL	One month	0.831	0.081	5
BEL	Two months	0.744	0.256	4
<i>Note: Nominal p-values are shown for transparency only and are not interpreted as confirmatory because of the short, serially dependent series.</i>				

Reported cost-savings estimates on the monthly forms rose from INR 1,178 lakh to INR 4,892 lakh for HAL and from INR 800 lakh to INR 6,000 lakh for BEL (the latter equivalent to INR 8 crore and INR 60 crore, respectively,

at the endpoints). These figures are reported organisational estimates. The records available for this analysis do not establish that the changes are attributable exclusively to digitalisation or to environmental digitalisation, so they are treated as operational context rather than environmental outcomes.

5 Discussion

5.1 Environmental parameters progressed alongside production digitalisation

The first result is that environmental implementation did not consistently lag the non-environmental production digitalisation comparator in either case. After excluding the overlapping P6 Energy & Sustainability category and renormalising the P1–P5 weights, the mean adjusted PDI–EDI gaps were 6.3 index points for HAL and 5.1 for BEL. The monthly trajectories were not uniform: HAL’s EDI was below the adjusted PDI in May and June, slightly above it in July and August, and below it again in September and October. BEL’s EDI was above the adjusted PDI in May, below it from June through September, and equal to it in October. These are descriptive differences between study-specific indices, not evidence of statistical parity or equivalence. The pattern is consistent with environmental functions progressing within the shared assessment environment, but the two-case design cannot identify the effect of the mandate.

From an institutional perspective, the pattern is compatible with the possibility that explicitly assessed environmental parameters receive organisational attention within a mandated programme. However, the study has no counterfactual and cannot isolate the mandate’s effect. The finding should therefore be read as evidence of implementation occurring under a common reporting framework, not proof that the mandate caused the observed trajectory.

5.2 Environmental process parameters and traceability are distinct

The comparison between EDI and the harmonised DTI shows that the selected environmental process index exceeded the two-item traceability index in five of six months in each organisation. The mean EDI–DTI gap was 25.5 points for HAL and 14.6 for BEL. In BEL, the gap narrowed to approximately zero in September and was 5.5 points in October; in HAL, it narrowed to 19.7 points by October. This is a descriptive asymmetry in the selected measures. It is compatible with, but does not test, the NRBV distinction between pollution prevention and product stewardship [4]. It does not establish that monitoring precedes, enables or causes traceability.

The interpretation must remain bounded. The index comparison does not demonstrate that environmental monitoring causes traceability to develop, nor that traceability is necessarily a later-stage capability in all manufacturing settings. The two indices contain different items and represent related but non-equivalent constructs. The results support the more limited conclusion that the selected environmental process parameters and common traceability parameters followed different implementation trajectories in these cases.

5.3 Implementation maturity is not environmental performance

The study's principal methodological contribution is the separation of implementation completion from environmental outcomes. EDI captures reported completion of selected environmental digital functions; it does not measure tonnes of waste avoided, energy saved, water conserved or greenhouse-gas emissions reduced. Reported man-hour and cost figures provide operational context, but the source records do not establish a direct environmental benefit or a causal link to EDI.

This distinction is important for sustainability assessment. A digital system may be installed or recorded as complete without being used consistently, and a productivity improvement may coexist with increased throughput or additional digital infrastructure burdens. Prior reviews similarly caution that the environmental implications of manufacturing digitalisation depend on both application-level benefits and technology-lifecycle impacts [1–3].

5.4 Implications for sustainability assessment and policy

First, sustainability assessments of digital manufacturing should distinguish implementation indicators from measured environmental outcomes. Completion ratios can serve as implementation indicators, but should be paired with operational measures such as material intensity, energy intensity, waste generation and emissions wherever these data are available.

Second, environmental process parameters and traceability parameters should be reported separately when the assessment instrument includes both. A single composite score may conceal whether an organisation has progressed in in-process environmental management, lifecycle information or both.

Third, the two-case comparison illustrates how a common reporting framework can make selected trajectories observable, while meaningful benchmarking still requires harmonised parameter definitions and transparent treatment of missing or non-comparable items.

Finally, evaluation windows should distinguish implementation dates from the dates at which operational benefits are recorded. The exploratory correlations in this study are insufficient to specify a general lag, and the reporting convention for the monthly MH/year estimates is not fully resolved. They therefore motivate more careful measurement in future studies rather than a claim about benefit timing.

5.5 Sustainable Development Goal relevance

The study has potential thematic relevance to SDG 9 and SDG 12. The mapping is deliberately limited to targets for which the assessed functions offer a defensible conceptual connection. It is not an evaluation of SDG progress: the study measures implementation completion and does not report the environmental outcome indicators needed to establish changes in resource use, waste generation or emissions. Table 6 distinguishes the observed measures from the claims that they can support.

Table 6
Bounded mapping between the study measures and selected SDG targets.

SDG target	Relevant study measure	What the evidence supports	What it does not establish
SDG 9.4 Upgrade infrastructure and retrofit industries for sustainability and resource-use efficiency	PDI and EDI trajectories; environmental digitalisation sub-parameters	The two cases recorded implementation progress in selected environmental digital functions during the observation period.	The study does not measure resource-use efficiency, industrial emissions, or the environmental effect of the retrofit.
SDG 12.2 Sustainable management and efficient use of natural resources	Material-utilisation monitoring completion ratio	The assessment records document implementation of a material-utilisation monitoring function.	The study does not quantify material consumption, material intensity, or resource savings.
SDG 12.5 Reduce waste generation through prevention, reduction, recycling and reuse	Waste-reduction automation completion ratio; selected traceability functions	The assessment records document implementation of waste-related digital functionality and selected traceability functions.	The study does not measure waste tonnage, recycling rates, material recovery, or circularity outcomes.
<i>Note: The mapping indicates thematic relevance, not measured SDG performance.</i>			

5.6 Limitations

The study has several limitations. First, it covers two organisations and six-monthly observations, so findings are case-specific and cannot support broad statistical generalisation. Second, the monthly observations are repeated measures and likely serially dependent. Third, EDI and DTI are study-specific unweighted means of selected completion ratios, not validated scales; the DTI harmonisation uses only two common traceability items and does not capture the full traceability domain. Fourth, reported cost and MH/year figures are approximate organisational estimates; the available records do not clarify whether month-to-month values are incremental, cumulative or revised estimates, and they are not independently audited in this study. Fifth, lagged correlations are based on very small samples and trending series; they cannot establish temporal precedence or causality. Sixth, no direct environmental outcomes—such as energy consumption, material intensity, waste tonnage or emissions—were available. Finally, the cases share one national institutional context and a strategically protected sector, limiting transferability. In addition, the original organisation-reported PDI includes an Energy & Sustainability category that overlaps with EDI. The principal comparison therefore uses a P1–P5 adjusted comparator; this adjustment removes the direct category overlap but remains a study-specific sensitivity measure.

6 Conclusion

This study examined environmental digital capability development under a common mandated Industry 4.0 and Quality Assurance 4.0 assessment framework, using monthly administrative records from HAL and BEL for May–October 2025. Using a production comparator that excludes the overlapping Energy & Sustainability category, the mean adjusted PDI–EDI gaps were 6.3 points for HAL and 5.1 for BEL. The monthly trajectories differed, and EDI exceeded the harmonised two-item DTI in five of six months in each organisation. The gap

between environmental process implementation and traceability narrowed toward the end of the observation period, although the two indices represent different and limited sets of functions.

The findings contribute a sub-parameter-level view of digital implementation and demonstrate the importance of separating environmental process capability, traceability and reported operational productivity. The PDI–EDI comparison also illustrates the need to check composite indices for shared components before interpreting differences between them. The study does not show that digitalisation caused reductions in environmental impacts, nor does it establish a universal sequence between monitoring and traceability. The practical implication is that implementation assessments should report distinct capabilities and, wherever possible, link them to independently measured environmental outcomes.

Future research should extend the observation period, include a broader range of manufacturing organisations, harmonise the definitions of environmental and traceability parameters, and connect implementation records with measured energy, material, waste and emissions outcomes. Such designs would allow researchers to examine whether the implementation trajectories observed here are associated with sustained environmental improvement.

Declarations

Funding. No external funding was received for this study.

Competing interests. The authors declare that they have no competing interests.

Ethics approval. The study uses organisation-level assessment and performance records and contains no individual-level personal data or human-participant responses. No individual was recruited or surveyed. Ethics approval was therefore not required.

Clinical trial number: not applicable

Consent for publication. The manuscript contains aggregated organisational data and no individual-level data or identifiable personal information. Organisational permission for data collection and use was obtained from HAL and BEL.

Data availability. Selected processed data supporting the reported indices are provided in Supplementary Material 1. The full processed dataset and analysis code are available from the corresponding author on reasonable request, subject to applicable organisational and government disclosure restrictions. The original assessment records are not included because they are subject to those restrictions.

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Author contributions. Dr. Catherine Julie Aarthy C: Conceptualisation, methodology, data extraction, data curation, formal analysis, interpretation, visualisation, writing—original draft, and writing—review and editing.

Dr. Smriti Verma: Data collection and consolidation, literature review, validation, and writing—review and editing. Both authors read and approved the final manuscript.

All authors reviewed the manuscript critically, approved the final version, and agreed to be accountable for the work.

Generative AI tools were used to generate code to extract data from monthly PDF reports of HAI and BEL, analyse the data, structural editing and enhancement of figures. The author verified the underlying data, calculations, source traceability, interpretation and final manuscript and remains responsible for the content.

Supplementary information. Supplementary Material 1 provides the selected source-derived monthly parameter series, index calculations and data dictionary supporting Tables 1–6 and Figs. 1–2.

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Figures

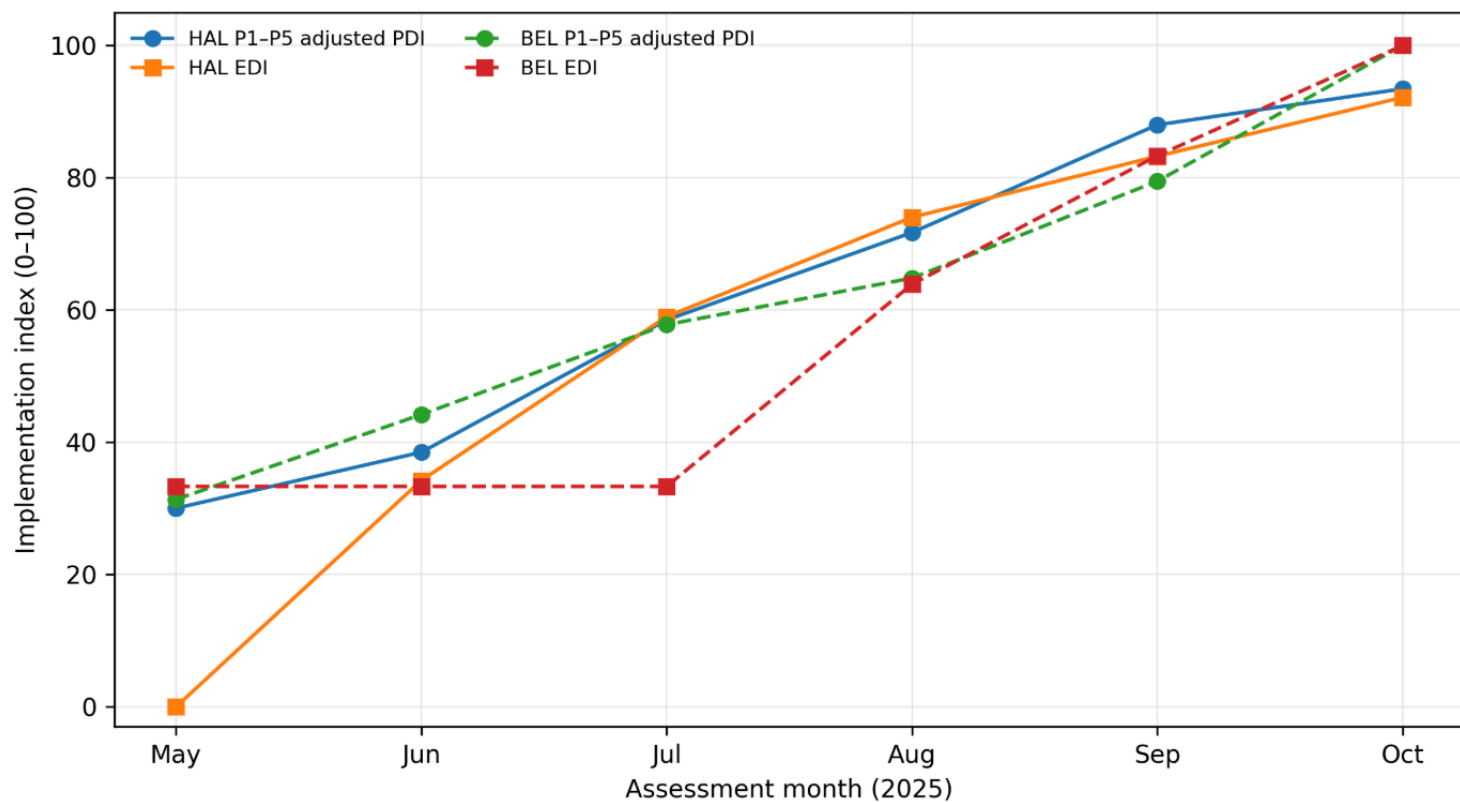


Figure 1

Production and environmental digitalisation trajectories in HAL and BEL, May–October 2025

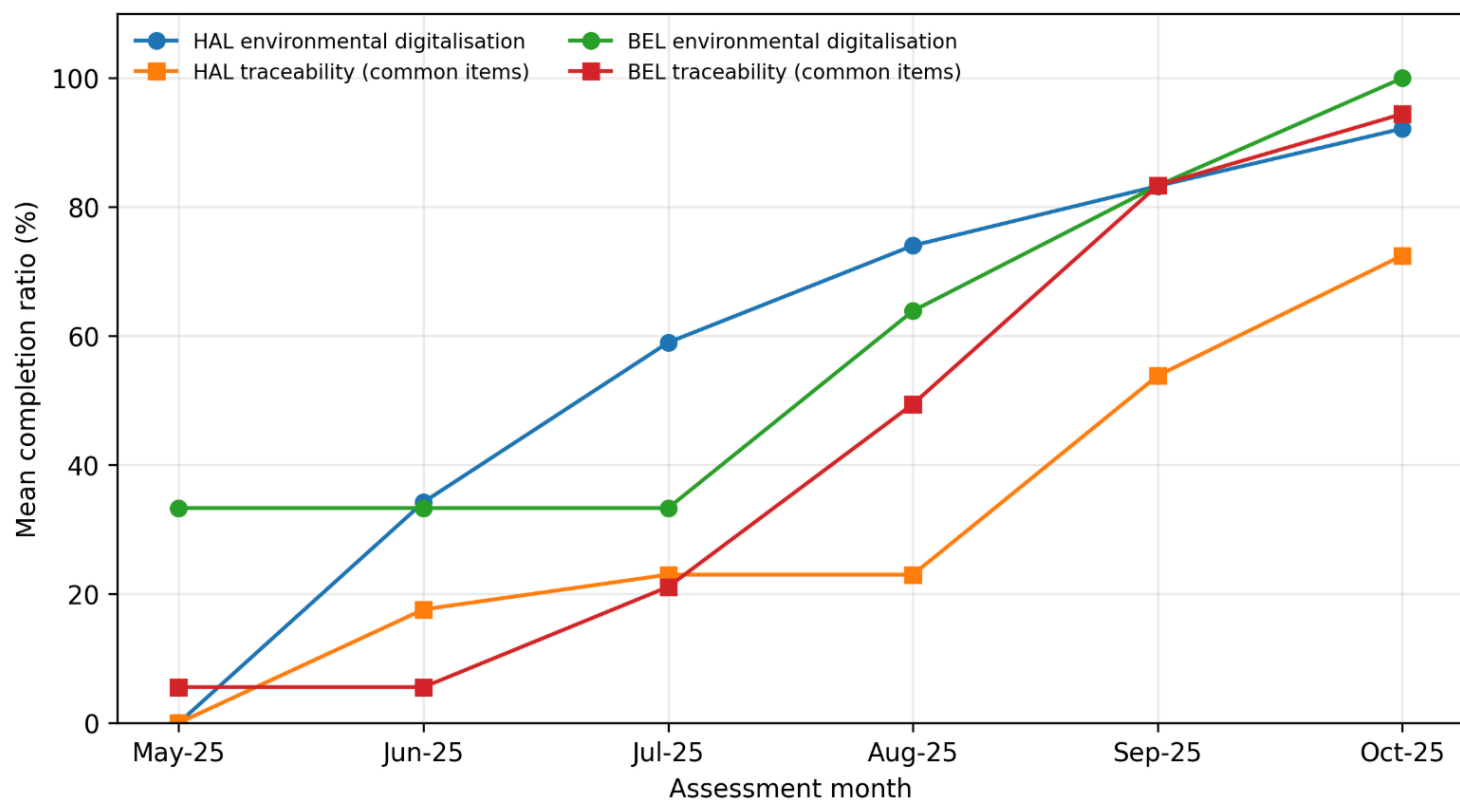


Figure 2

Supplementary Files

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