| Authors (Year) | Main I4.0 technology | Solution | LSS tool (DMAIC phases) enhanced or replaced\* | Outcomes and Benefits | Research Method |
| --- | --- | --- | --- | --- | --- |
| Abed et al. (2020) | IoT (3D cameras, sensors) | >Deep lean approach based on DMAIC >IoT technologies supported by neural networks that analyses real-time sensor data to detect anomalies and forecast process deviations >Deep imaging using 3D analysis by a binocular stereovision to monitor eddie's movement lines and detect bubbles to eliminate them. >DOE to identify optimum values for significant factors (input for ANN)  >ANN (with back-propagation) for prediction and optimisation | >Data collection (M) >Poka Yoke (I) | >Reduction of defective output by 92.8% >A smart machine that controlled all impact input variables reduced defective bathtub rates to less than 0.08%. >NN interventions increase process reliability | Case Study |
| Johnston et al. (2009) | ANN / Matlab | >Neural networks to improve downstream performance >Identification of predictor values using a Six Sigma methodology for the training of the ANN. >three-layer feed forward back propagation with 10 neurons in the hidden layer with resilient back propagation algorithm as training function >Mean squared error (MSE) performance function  >Levenberg-Marquardt training function for optimisation | >Regression (I) | >Network model can predict output values with an accuracy of 98%, i.e., the model explains 98% of the variation >Positive impact on cycle time, yield loss and cost-effective production | Case Study |
| Lin et al. (2012) | ANN (BPNN, k-means) | >Construction of artificial neural network >API algorithm to optimise the critical parameters >Levenberg-Marquardt (LM) algorithm for BPNN learning >Integration with Taguchi experimental design to determine optimal parameters | >Taguchi Design (A) | >Cpk was improved from 0.89 to 1.63 >Prediction results can reach 97.6% and more vs. accuracy rate of the trial and error method of 96.6% | Case Study |
| Mishra and Rane (2019) | ANN | >Analytics with Six Sigma DMAIC approach: prediction model building and simulations >Design of experiments, artiﬁcial neural network and the technical simulations >Logistic regression model for predicting casting quality level | >DOE (A) >Root-cause analysis (A) | >Prediction model enhanced root-cause analysis for defective casts >Rejection rate reduced by 99%, i.e. savings of 6.6 million INR p.a. >On-time delivery of 99.78 per cent | Case Study |
| Satsangi et al. (2013) | ANN | >Prediction of casting defects using a multi-layer feed-forward network with back-propagation learning algorithms >Multi Variable Linear Regression (MVLR) and Artificial Neural Network (ANN) | >Taguchi Design (A) | >Significant reduction in casting defects and product quality improvement | Case Study |
| Sen (2015) | ANN / Matlab | >ANN in DMAIC to predict the concentration of CO (output)  >Multilayer perception (MLP) with feed-forward architecture >Log-sigmoid transfer function (LOGSIG) | >Principal component Analysis (A) | >Significant process parameters responsible for CO emission identified >Process capability is improved from 0.80 to 1.18 >Annual savings of approx. 50 million INR >Energy consumption by the blast furnace drops 2.58% | Case Study |
| Su et al. (2019) | ANN and Generic Algorithm | >Simple neural network with only one hidden layer >Generic algorithm to optimise settings of parameters | >RSM\* (I) | >10 experiments through computer-aided engineering (CAE) have shown that NN + GA outperforms RSM >NN with GA are able to solve the parameter optimisation problems given that learning rate, momentum coefficient and number of nodes are well selected. >Cost savings of approx. $2.9 million USD p.a. >Reduction of defective rate from 15.73% to 0% | Case Study |
| Uluskan (2020) | ANN | >Thermal camera to detect which refrigerators do not comply with power specifications >ANN with 100 neurons in the hidden layer >Taguchi loss functions >Maximum likelihood function >Logistics regression function >Monte Carlo cross-validation to compare methods | >Taguchi loss function\* (A) >Logistic regression\* (A) | >ANN outperforms all other solutions as it can model non-linear and complex relationships between inputs and outputs. | Experiment |
| Zgodavova et al. (2020) | ANN / Matlab | >Intelligent SPC using ANN and ML to automatically detect when a process is out of control and to estimate the process mean and variance >ANN with one hidden layer and ten neurons with hyperbolic tangent sigmoid activation function and output layer with one neuron with a linear activation function >Prediction model to indicate when machine settings should be adjusted to reduce process variation | >Regression\* (A) >SPC (C) | >Prediction of CTQ characteristics from input factors indicates when to adjust machine settings to compensate for variation caused by input material >New control scheme that helps reduce process variation and increases process capability >ANN model shows better accuracy than the polynomial regression model | Case Study |
| Belhadi et al. (2021) | BDA | >Novel framework integrating BDA and Green LSS >Multi Perceptron Layer (MLP) to enable predictive maintenance >Random Forest algorithm showed the best performance compared to other algorithms >Support Vector Machine to improve prediction accuracy >Lagged Dependent Variables for higher prediction accuracy >One-class classification based control charts using k nearest-neighbours data description algorithm >Real-time notification system (predictive analytics) >Self-assessment tool to assess organisational readiness | >Statistical analysis (A) >Parameter tuning (I) >Control Chart (C) | >BDA-GLSS enhances companies' technological readiness and environmental capability >Real-time quality control, event-based inspection, and predictive maintenance enabled >Reduction of complexity | Case Study |
| Fahey et al. (2020) | BDA / R | >Novel framework combining Six Sigma and Business Analytics. >Random Forest algorithm in R >Variable Importance Plot >Symbolic Aggregate Approximation (SAX) >Analytics toolkit with email notification for control limit breaches >Digital twin approach | >Cause and Effect diagram (M) >Simulation (A)  >Process Monitoring (C) | >The framework is a hybrid approach which integrates BDA with Six Sigma >It helps to overcome Six Sigma limitations and Big Data challenges | Case Study |
| Koppel and Chang (2021) | BDA | >A new Six Sigma approach (MDAIC) that combines massive data generated by manufacturing environments to identify improvements. >SPM tools, such as continuous and proﬁle monitoring algorithms and attribute control charts to monitor system processes and identify issue areas >MapReduce algorithm to analyse large sets of different data types | >Data collection (M) >Control Chart (C) | >The unified platform for monitoring process performance helps identify and prioritise continuous improvement projects >All process information is provided to plant and department managers at an appropriate level of detail | Simulation study |
| Laux et al. (2017) | BDA / Hadoop, R | >A Framework that integrates BDA techniques into DMAIC phases >Hadoop for pre-processing >R for Data Analysis | >VOC (D) >Data analysis (A) | >Framework combining Six Sigma and BDA principles could enhance student success | Conceptual study |
| Sanchez-Marquez and Jabaloyes Vivas (2020) | BDA / Matlab | >Multivariate SPC charts based on predictive models >Enhanced PLS algorithm combined with a bootstrap technique for small samples >MATLAB script | >Regression (A) >SPC chart (C) | >Improves detectability over the traditional univariate and multivariate SPC approaches >Gaining key insights into customer characteristics leads to reduced number of potential defects | Case Study |
| Shanshan et al. (2021) | BDA / Text mining | >Research topic mining using LDA (Latent Dirichlet Allocation) analysis on research titles by teacher >Full use of web data though text analysis, knowledge graph analysis | >Data analysis (A) | >A course topology graph for each management school >A knowledge graph for each course in each school >Guideline for implementing an intelligent curriculum system improvement method following the DMAIC approach | Conceptual and case study |
| Shivajee et al. (2019) | BDA | >Framework to identify and analyse elements of manufacturing conversion cost >Data acquisition (SCADA) and SAP as recording system  >Low-cost sensors record real-time data stored in a cloud >Big screen to monitor deviations of key variables from the standard | >Data collection (M) | >Total annual saving of USD 2.2 million >Statistical analysis to identify the changes in signals from the sensors enhances tool life | Case Study |
| Sungbum Park and Kang (2016) | BDA | >New paradigm of LSS, "3S paradigm" (simple, speedy and smart’) >Simplified 5 steps instead of 15 steps >Integration with IT, Big Data, AI, Cloud and IoT | >Statistical analysis (A) | $ 9 success factors for new paradigm ‘3S LSS’ | Conceptual and case study |
| Azadeh-Fard et al. (2019) | CRISP-DM | >Framework integrating cross-industry standard process for data mining framework (CRISP-DM) and Six Sigma to detect abnormal hospital LOS. >Root-cause analysis for diagnosing which subsystem contributed to an abnormal length-of-stay >Perform SDCA (standardise-do-control-act) cycles to improve the identified process | >Control chart (C) | >The 15 steps in CRISP-DM model can enhance Six Sigma and CI projects. >The framework provides in-detail guidance for healthcare providers how to reduce abnormal LOS. >Cost reduction due to monitoring and minimising LOS. | Research and Case Study |
| Gaudard et al. (2009) | Data mining / JMP statistical software | >Partition platform in JMP for of classiﬁcation and regression tree analysis >Recursive partitioning, a variant of regression and classiﬁcation tree analysis >'custom design platform', functionality for generating complex experimental designs | > Root-cause analysis\* (A) >DOE (A) | >The defect could be eliminated through root cause identification >The split-plot experiment designed in the JMP custom design platform identified relevant two-way interactions. >Recursive partitioning informed choice of factor levels for DOE and reduced number of experiments. >Using partitions addresses some of the limitations of multiple linear regression and logistic regression. | Research and Case Study |
| Ghosh and Maiti (2014) | Data Mining / Decision tree algorithm / SPSS statistical software | >Framework based on DMAIC that integrates Data Mining techniques >Decision tree algorithms: classification and regression tree (CART), chi-squared automatic interaction detection (CHAID) | >DOE (A) >Regression\* (A) | >Selection of the most important variables for reduces the DOE scope and therefore saves time and costs > Cost savings p.a.: USD 0.28 million from defect reduction of cylinder head casting. | Research and Case Study |
| Hsiao et al. (2016) | Data Mining / Decision tree algorithm / SPSS statistical software | >Framework based on DMAIC that integrates Data Mining techniques >Decision tree algorithm: chi-squared automatic interaction detection (CHAID) | >Cause and effect diagram\* (A) | >Complaint management framework helps anticipating customer complaints and taking preventive actions to avoid defective service >Reduction of service defects lead to long-term benefits, i.e., cost and time savings, increased service operations quality | Research and Case Study |
| Morlock and Boßlau (2021) | CRISP-DM | >Framework combining DMAIC phases and tools with CRISP-DM model  >ML model that determines optimal combination of parameter settings to maximise output volume | > DoE (A) | >OEE improvement and therefore increase in production capacity | Conceptual and case study |
| Schäfer et al. (2019) | CRISP-DM | >Holistic Six Sigma 4.0 process model integrating data mining into DMAIC >Neural network as prediction model containing predictive algorithms | > Root-cause analysis\* (A) | >The Six Sigma 4.0 model combines Six Sigma and data mining methods with respect to zero defect management in production processes. >By combining the strengths of both concepts, the framework can guide improvement projects in manufacturing. >The prediction model has been successfully validated in a real-world improvement project (electronics manufacturing). | Research and Case Study |
| Tay and Loh (2021) | CRISP-DM | >Unified framework that integrates DMAIC and CRISP-DM for supply chain >Various I4.0 technologies, e.g. IoT, Cloud Computing, Big Data as supporting technology >Iterations in DMAIC cycle (agile DMAIC) >Data scientist is part of LSS project team | >VoC (D) >VSM (M) >Process map (M) >Poka Yoke (I) | >Powerful fact base for negotiations with carriers and Logistics Solution Providers (LSPs) >Good practices for “Innovation” and “Standards and Routine” | Case Study |
| Yang et al. (2009) | Data Mining / classification and decision tree / SPSS | >Use data mining classification algorithm and decision tree to forecast number of physicians needed in the emergency room. >A forecast performance evaluation matrix based on cost loss as per Taguchi's Loss Function helps to continuously improve and control staffing. | >Statistical analysis (A) >Simulation\* (I) >Process Monitoring (C), Taguchi's Loss Function (C) | >The continuous improvement of human resources utilisation resulted into a cost decrease of 37%. | Case Study |
| Zwetsloot et al. (2018) | Data Science/ Data Mining | >Modification I: Data scientists work for LSS organisation in "data science LSS" projects >Modification II: Integrate CRISP-DM in the DMAIC roadmap >Modification III: Interdisciplinary training of data scientists and LSS belts | >Statistical analysis (A) | >LSS-DMAIC roadmap adapted to the changes brought about by the digital age >LSS belts and data scientists are trained in each other's fields so they can work together on improvement projects. | Case Study |
| Abed et al. (2020) | IoT (3D cameras, sensors) | >Deep lean approach based on DMAIC >IoT technologies supported by neural networks that analyses real-time sensor data to detect anomalies and forecast process deviations >Deep imaging using 3D analysis by a binocular stereovision to monitor eddie's movement lines and detect bubbles to eliminate them. >DOE to identify optimum values for significant factors (input for ANN)  >ANN (with back-propagation) for prediction and optimisation | >Data collection (M) >Poka Yoke (I) | >Reduction of defective output by 92.8% >A smart machine that controlled all impact input variables reduced defective bathtub rates to less than 0.08%. >NN interventions increase process reliability | Case Study |
| Arcidiacono and Pieroni (2018) | IoT | >Integration of I4.0 technologies into DMAIC framework >Network with interconnected sensors and devices >Wearable devices for patient data collection >IoT modules with sensors and tablets and smartphones for monitoring | >Data visualisation (D) >Data collection (M) >Root-cause analysis (A) >Process Monitoring(C) | >LSS4.0 enables more effective performance measurement >Big data allows to overcome limitations of traditional customer analysis tools >Registration in real-time and instant information on available beds >Enhanced analysis of causes for delay or anomalous waiting times and monitoring of the CTQs | Case Study |
| Chiarini and Kumar (2021) | IoT | >Framework how to best integrate LSS methods and Industry 4.0 technologies >Smart sensors and IoT to support some of the Lean tools >COBOTS, AMR/AGV, VR, for automation, standardisation and error reduction >Smart VSM for identifying improvements based on Industry 4.0 | >VSM (A) >5S (I) >Poka Yoke (I) | >Automatic cost and accounting system replaces activity-based costing >I4.0 and LSS can be integrated so competitive advantage is achieved | Conceptual study and Case Study |
| Fernandez et al. (2021) | IoT | >Predictive Maintenance supported by IoT Technology >Predictive Maintenance Process Flow Chart and System Design Process >Live graphical analytics and reporting dashboards | >Process redesign (I) >Visual Management (C) | >Increased ratio for predictive maintenance vs. Conventional maintenance from 84:16 to 95:05 >Real-time asset condition and monitoring and control without human intervention >Condition-based monitoring, and maintenance analytics and reporting dashboard | Experiment |
| Chi et al. (2007) | Machine Learning / MATLAB | >Automated Intelligent Manufacturing System (AIMS) using MATLAB with regression support vector machines for model construction and a generic algorithm for optimisation | >DOE\*(A)  >RSM\* (I) | >AIMS enables a faster and less costly analysis of interactions and effects compared to DOE and other statistical tools.  >Insights provided by machine learning models help adjust input settings and configurations to increase performance. | Experiment |
| Giannetti and Ransing (2016) | Machine Learning / UCI | >UCI Machine Learning library >Quantile regression tree algorithm to ﬁnd optimal tolerance limits >Bootstrap method to predict process robustness >Noise reduction through Principal Component Analysis >7Epsilon with 7 steps | Regression (A) | >Novel mathematical formulation of the tolerance synthesis problem predicts the process robustness while accounting for risks | Research and Case Study |
| Palací-López et al. (2020) | Machine Learning / Matlab (MEDA) | >Multivariate Exploratory Data Analysis (MEDA) Toolbox >MVBatch Toolbox >Intelligent monitoring system that alerts on out-of-speciﬁcation batches | >PCA (A), PLS (A) >Process monitoring (C) | >Cost-savings of > EUR 140.000 p.a. >PCA reduces the complexity by identifying factors with the biggest impact on output variables. >PLS-regression model for predicting CQCs from the summary variables | Case Study |
| Graafmans et al. (2021) | ProcessGold PM software | >PMSS (Process Mining for Six Sigma) framework and guideline >Tool implementation using ProcessGold software >Process Mining Project Methodology (PM2) >Dashboards created for each DMAIC phase >Case study for invoice process | >SIPOC (D) >Data collection (M) >Process Map (A, C) >Root-cause analysis (A) >Process redesign (I) >Process monitoring (C) | >PMSS is a structured guideline with tool support for practitioners >Identification of bottlenecks and root-causes for problems >Detection of new process variants or non-regular process executions | Design Science Research with single case study |
| Kregel et al. (2021) | ProM Process Mining software | >Implementation of a process mining solution to support DMAIC phases using agile methodology >Process data from ERP system, BI system and office software >Case study for manufacturing process | >SIPOC (D) >Data collection (M) >Process Map (A, C) >Root-cause analysis (A) >Process redesign (I) >Process monitoring (C) | >74% fewer machine process steps needed in a high-cost production line >Process data (high volumes, unstructured data) becomes transparent >Identification of bottlenecks, idle-times and process deviations >Faster project completion than with traditional Six Sigma project | Design Science Research with multi-case study |
| Ramires and Sampaio (2021) | Celonis Process Mining software | >Implementation of a process mining solution to support DMAIC phases according to framework adapted from Graafmans et al. (2021) >Process data from ERP system >Definition of key performance metrics and implementation of a dashboard >R for statistical analyses to study correlations between different variables. | >Process Map (D) >Data collection (M) >Multivariate regression (A) >Process redesign (I) >Process monitoring (C) | >Procurement process of a hospital improved >Found 200 redundant orders issued yearly with a total cost of 1,600 euros >Reduced ordering time by 25% and decrease the probability of issuing redundant orders by 70% | Case Study |
| Shin et al. (2019) | Process Mining / DISCO software application | >Manufacturing process data from FPSO topside module (planned and actual production schedules) >Fuzzy mining technique (DISCO) to design process model >Conformance checking through event logs | >Process Map (A, C) >Root-cause analysis (A) >Process redesign (I) >Process monitoring (C) | >Identified bottle necks, delays, idle times etc. in production and outsourcing process >Insights were used to standardise the work process and develop a decision support system for changes in the production schedule | Case Study |
| Singh et al. (2021) | Process Mining / DISCO software application | >Integration of process mining solution with LSS using Plan, Do, Study and Act (PDSA) Cycle approach >Modified SMED concept (one-user, one-machine) to Multi-Machine Setup Reduction (MMSR) to accommodate the hospital structure | >Process Map (A, C) >Root-cause analysis (A) >SMED\* (I) >Process redesign (I) >Process monitoring (C) | >Reduction of turnaround time for eye surgeries and increased number of surgeries from 20 to 32 >Better utilisation of the hospital staff and resources >Collaboration Table’ tool developed for the shared environment | Case Study |