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AI Enabled Multipurpose SPM Design Considerations

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Abstract: SPM are unique machines and hence cannot be generalized while designing an SPM special approach has been adopted keeping in mind that the desired purpose for which it was designed has been accomplished. Unlike general-purpose machines, SPM are tailored to meet unique operational requirements whether it's drilling, grinding, welding, milling, tapping, or inspection. In addition to it as industries across the globe accelerate their adoption of smart manufacturing and automation, the design of SPM has become a critical engineering discipline. This paper certainly explores the essential design principles that ensure these machines deliver performance, reliability, and compliance across global markets.

Keywords: Special Purpose Machine (SPM), Precision Machine Design, Industrial Automation, Mechatronics, PLC-Based Control, Servo Motor, Machine Vision, Design Optimization, Cycle Time Reduction, Industry 4.0.

INTRODUCTION

SPM are the basic building blocks of modern manufacturing which can automate the production by optimization. The recent developments in SPM are not limited to achieve optimization, reduced cycle time etc but it can be well developed fulfilling the requirements for Industry 4.0. These machines are automatic machines so designed to operate continuously for 24 hours a day, with minimum supervision. The special purpose machine is generally product specific and they are required to be designed and developed for every specific requirement in industries however it may also be possible to cater multiple jobs at a time with similar features yet differing in dimensions by using change tooling concept.
Whereas in case of design of general-purpose machines mostly the designed standards are fixed as per the present requirements/ existing demands of the market. However, since the market requirements are not consistent with passage of time and hence due to evolution of dynamics in the market the need of SPM design comes into picture. The design of New SPM is a kind of research activity where the designer has to fulfil the customer custom requirements without compensation the engineering and management desires. Thus it becomes very crucial for designers to go with various designing phases for SPM development and fulfil the customer demand as per the time. The uniqueness in SPM design defines the special purpose for which it get designed and achieves the desired purposes. The uniqueness includes accuracy, resolution, quality, cycle time, return on investment etc.

USPS OF SPM

- High Productivity
- Reduced Cycle Time
- Multi-Operation Capability
- High Precision and Repeatability
- Customized Design
- Automation-Ready
- Reduced Labour Requirement
- Lower Production Cost
- Integrated Quality Inspection
- Modular Design
- Reduced Material Handling
- Energy Optimization
- Predictive Maintenance Capability
- Industry 4.0 Connectivity
- AI-Based Optimization
- Fast Return on Investment

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SPM DESIGN KEY PARAMETER

SPM Key Parameters	
Category	**Key Parameters**
Workpiece	Material, size, weight, geometry, batch size
Process	Type of operation, number of operations, operation sequence
Productivity	Cycle time, production rate, throughput, OEE
Machining	Spindle speed, feed rate, depth of cut, cutting speed
Cutting	Cutting force, torque, spindle power
Accuracy	Dimensional accuracy, positioning accuracy, repeatability
Surface Quality	Surface roughness, waviness, form accuracy
Machine Structure	Stiffness, rigidity, deformation, natural frequency
Vibration	Amplitude, frequency, damping, resonance
Tooling	Tool type, tool life, tool wear, tool-change time
Fixture	Locating accuracy, clamping force, repeatability
Drive System	Motor power, torque, speed, acceleration
Motion	Stroke, travel, velocity, acceleration, positioning time
Automation	PLC, HMI, sensors, actuators, servo control
Inspection	Sensors, gauges, machine vision, inspection time
Energy	Power consumption, energy/component
Reliability	MTBF, MTTR, machine availability
Maintenance	Maintenance frequency, downtime, accessibility
Safety	Guards, interlocks, emergency stop, safety sensors
Economics	Machine cost, operating cost, maintenance cost, ROI

LITERATURE REVIEW

The literature indicates a clear evolution from conventional dedicated SPMs toward intelligent, automated, sensor-based and reconfigurable manufacturing systems. Existing studies provide strong foundations for machine design, optimization, feasibility analysis, and automation. Recent AI research provides additional opportunities for real-time quality control, predictive maintenance, process optimization, and intelligent decision-making. The exhaustive literature study has been carried out on design and fabrication for SPM. The findings of various scholars in the field of design, fabrication and analysis of SPM have been presented below:

1. P. R. Sawant et al.(March 2012) – Developed machine which has main objective was to drilling and tapping of TATA cylinder block which has 8 drills in which 7 holes of Ã˜6.75mm and one of Ã˜ 12mm also linear tapping operation for Ã˜12mm and angular tapping operation for Ã˜ 5.1mm. It saves time for loading and unloading due to use of hydraulic clamping and increases production rate, less rejection of work due to automatic control.
2. Manish Kale et al. (June 2015) – Studied on Design, fabrication and analysis of SPM for reaming and drilling. In this situation study they develop SPM for riveting and drilling of the work-piece of different sizes and thickness. The SPM uses pneumatically operated cylinder for drilling riveting operation. They also use ANSYS for checking stress analysis. The case study concludes that SPM is beneficial as it reduces process time.
3. Nikhil J Surwad et al. (2015) – Studied on design and develop a special purpose machine capable of performing trimming and drilling operations altogether on the tail lamp bracket casting of a motor cycle. In this study the design is to trim out the flashes generated after pressure die casting process from 14 different areas of the casting and to drill 2 holes on the same casting.
4. Prof. Chukwumuanya et al. (November 2016) – Investigated Design and develop multiple spindle drilling head for mass production of Peugeot 504 automobile brake drum. In this design they developed multi-spindle drilling head for drilling 6 holes at a time, in which 4 holes of Ã˜14.5mm and 2 holes of Ã˜8.5mm. They analysis the various gear forces theoretically. It concludes that mash increases production rate as compare to individual drilling operation.
5. Prof. A. A. Shingavi et al. (March 2018) – Concentrated on configuration and improvement of multi spindle drilling head for process duration advancement of the part and examination of efficiency of segment utilizing ordinary

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outspread penetrating machine and unique reason machine. It reasoned that by utilizing multi spindle penetrating head profitability will increment. Probability of opening missing is killed, in light of the fact that six gaps penetrated at once. The expense per piece is diminished.

6. A.S.Udgave et.al. (March 2018) – In this paper author studies and tries to study attachments for the radial drilling machine to make it special purpose machine. This will increase productivity and also reduces time. In this paper work is done on the currently going on job as well as it includes industrial case study. Multi-spindle head is developed to drill two holes simultaneously in one setting only. Two spindles are driven by a single motor with mechanism of changing speed. Different mechanism is given to the table and spindle head to adjust according to work piece. Also this paper gives information about types of multi spindle drilling head.

7. Yaman Patel et.al (March 2018) – Studies different problems that are restricting mass production rate and develop a new drilling machine in which the main purpose is to minimize time required for drilling holes on different PCD and also paper deals with the improvement of cycle time.

8. P.O. Boucharda, et.al. (Aug 2008) – This pamphlet was published on Numerical modeling of self- pierce riveting from riveting process modeling down to structural analysis focused on the numerical modeling of the SPR process. They had used the finite element software to enables the model for large deformation of elastic plastic materials for 2D and 3D configurations. A Lemaitre coupled damage model had been implemented to deal with damage during the process and fracture was modeled using the kill element technique. They had also check the influence of the transfer of important mechanical fields, such as residual stresses or damage, on the final mechanical strength of the riveted specimen.

9. A.S. Aditya Polapragada, et.al (April 2015) – Published the paper on pneumatic auto feed punching and riveting machine in (IJERT). In this paper they had design and fabricate the unit and stated the importance of the pneumatic press tool had an advantage of working in low pressure, even a pressure of 6 bar was enough for operating the unit. The die used in this was fixed such that the die of required shape could be used according to the requirement. This enables them to use different type punch dies resulting in a wide range of products.

10. A. M. Takale et.al. (April 2015) – Was focused on Design & manufacturing of multi spindle drilling head (msdh) for its cycle time optimization, This paper deals with design and development of multi spindle drilling head for cycle time optimization of the component. Their attempts have to improve the productivity by reducing the total machining time and combining the operations. They have design the major components of multi spindle drilling head like main spindle gear and main spindle and calculate the stress analysis. By using multi spindle drilling head productivity will increase. Because with the present process one hole produces at a time requires 4 minutes for each component (because tool change takes place for drilling 5mm hole (for M6x1 tap)). i.e. 12-15 parts are produced during one hour, but by using multi spindle drilling head cycle time approximately takes place 1 minute.

11. Kaushar H. Barad et al (Oct. 2016) – Automated Of Conventional Radial Drilling Machine. They observed that by use of this automation manufacturer can drill holes easily, more accurately and in less time, with minimum errors so manufacturing cost will also reduce.

12. Sharad Srivastava et al. (June 2014) – Developed a conceptual model of a machine which would be capable of performing different operation simultaneously, and it should be economically efficient. In this machine we are actually giving drive to the main shaft to which scotch yoke mechanism is directly attached, scotch yoke mechanism is used for sawing operation. On the main shaft we have use bevel gear system for power transmission at two locations. Through bevel gear we will give drive to drilling center and grinding center. The model facilitates us to get the operation performed at different working center simultaneously as it is getting drive from single power source. Objective of this model are conservation of electricity (power supply), reduction in cost associated with power usage, increase in productivity, reduced floor space.

13. Prof. M.B. Bankar et al. (Jan 2013) – Studied Improvement in design and manufacturing of multiple spindle drilling attachment, in which they uses planetary gear system for drilling operation. This case study they briefly gives information From this review, it was found that no combine work has been carried out on the given subject, so we have carried out our work on the outline.

14. Pratik Parsania et al. (June 2013) – Studied on Design for Multi spindle drilling SPM. In this case study it is shown that how effectively SPM work as compare to conventional drilling machine. In conventional drilling machine it takes 8 hours for drilling 2400 pieces per day and by using it takes only 3.33hours for drilling 2400 pieces per day hence it is largely affects the production rate. Hence this case study concludes that use of SPM is most important in small scale industries.

15. Prof. Bajirao H. Nangare Patil et al. (May 2013) – Studied Design and development of gear box for multi-spindle drilling machine. This case study drilling of 26 holes of various sizes, are carried out on cylinder block. This study conclude that due to use of spur gear noise reduction, reduction in cycle time, increases production rate and also holes are drilled with required accuracy and tolerances are maintained.

16. Jiayin et al analyzed about Design of Three Degrees of Freedom Pneumatic Manipulator Based on PLC Control for eliminating the use of manipulator in the big factory

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17. Joy et al have develop a Switch Mode Power Supply (SMPS) that integrates with a battery that is charged by solar energy. The battery provides standby power of the requisite quality to the PC. Personal Computers (PC) need stable power inputs that can deliver rigidly regulated and isolated DC outputs of high power quality at different levels.
18. Mohammed Islam et al have designed VFD Motor Controller for Ship Service Auxiliaries. This chapter illustrates theVFD applications in an electrical system where the power generation is limited to a few megawatts
19. Patel et al have designed Special Purpose Winding Machine (SPWM) is capable of winding up to 30 mm 30 mm square cross section NbTi and Nb3Sn based cable-in-conduit-conductors (CICC) in both circular and non-circular (D shape) winding pack geometries
20. Wang et al designed an intelligent book sorting system based on PLC and touch screen control, comprehensively applies PLC technology, RFID technology, touch screen technology
21. Wijaya et al developed a pneumatic system with PLC control for the elimination of conventional tofu press machine
22. L. Patnaik and S. Kumar, "Design and development of a special purpose machine for glass insertion in plastic frame for spill guard glass shelf assembly of commercial refrigerators," 2017 International Conference on Advances in Mechanical, Industrial, Automation and Management Systems (AMIAMS), Allahabad, India, 2017, pp.144-150, doi: 10.1109/AMIAMS.2017.8069203.
23. W. Wijaya, D. Rosdiana, M. A. Fhaizal, A. Apriyani, W. Sani and R. Agusiady, "Utilization of PLC control on pneumatic powered tofu press machine," 2022 16th International Conference on Telecommunication Systems, Services, and Applications (TSSA), Lombok, Indonesia, 2022, pp. 1-4, doi: 10.1109/TSSA56819.2022.10063894

SUMMARY OF LITERATURE

Research area	Main focus
SPM design	Dedicated machine architecture and mechanical design
Feasibility	Technical and economic suitability
Optimization	Configuration, cutting speed, feed, time and cost
Reconfigurability	Improving flexibility and adaptability
Automation	PLC, robotics, sensors and automated operation
Machine vision	Inspection and defect detection
AI/ML	Prediction, optimization and intelligent decision-making
Predictive maintenance	Fault detection and downtime reduction
Economic analysis	Cost, productivity, ROI and payback

PROBLEM DEFINITION

Old-fashioned relay-based control systems and manual machines in industries face complex wiring, high maintenance, limited flexibility, and frequent human errors. Constant supervision leads to inconsistent quality, reduced efficiency, and higher labor costs. filling speed and pressurization speed of EPC are deduced, and the influence of external factors make them complex and difficult to handle and troubleshoot.
The main disadvantages of the traditional system are: Lack of Flexibility, High investment, Manual handling and quality inspection, slow speed of operations, fixed operating parameters, limited access and data monitoring etc.

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PRESENT SCOPE OF STUDY

Considering the above limitations, we can have PLC based automation and add AI enablement to make SPM compatible to I4.0 requirements. We can propose HMI as the master control panel allows operators to monitor and control various system parameters effortlessly, ensuring seamless operation and real-time adjustments. The automation of processes through PLC programming, relay control, and servo motor integration has eliminated the limitations of traditional manual and relay-based systems, reduced human error and increased productivity. Additionally, the modularity of the system allows for future scalability and adaptability to evolving industrial requirements. By implementing this advanced control system, the project successfully enhances operational efficiency, minimizes downtime, and optimizes overall process control, making it a highly effective and sustainable solution for industrial automation. AI and ML block allow to provide 360 degree feedback and accessibility i.e remote access making the system more accurate and optimized bringing end to end automation and improvised decision making of SPMs.

PRINCIPLES OF SPECIAL PURPOSE MACHINE (SPM) DESIGN

This is very important while designing the SPM Machines we should have a very transparent view or blue print has been designed first keeping the following design principals kept in mind.

1. **Manufacturing requirement (Why to Design)**
   - Potential Operations to be carried out example drilling, milling, turning, grinding, assembly, etc.
   - Kinds of Jos include material, dimensions, tolerance and production volume.
2. **Process planning (Design Adaptation)**
   - Poka Yoke. what will be the sequence of operations.
   - Tooling list out the appropriate cutting tools and process parameters as per the sequence of operations
3. **Expected Production Rate (ROI Parameter)**
   - What are the machining and cycle time requirements
   - List out simultaneous operations to reduce production time
   - How to minimize loading, unloading and tool-change time for getting better performances
4. **Expected Accuracy and repeatability (Quality Parameter)**
   - Plan the tolerance limits while defining the job dimensional accuracy.
   - Minimize positioning, alignment and geometric errors.
5. **Rigid machine structure (Machine Strength)**
   - SPM should have sufficient rigidity and strength to withstand cutting forces and vibrations.
   - Designed frames, columns, beds, and supports to achieve the required stiffness
   - Use appropriate structural analysis FEA (Finite Element Analysis), Static, Dynamic, Modal, Buckling, and Fatigue analysis.
6. **Job Holders and fixturing (Job Positioning)**
   - Ensure accurate and repeatable workpiece positioning.
   - Provide proper clamping.
   - Consider quick loading/unloading and fool-proofing.
7. **Tool selection and tool management (Tool Box)**
   - Select suitable cutting tools and tool holders.
   - Ensure proper tool accessibility.
   - Prevents **movement and vibration** during operation.
   - Clamping force should be sufficient but should **not damage or deform the workpiece**.
   - Allows **quick loading and unloading**.
8. **Automation (!4.0)**
   - Use PLCs, sensors, actuators, servo drives and HMIs where appropriate with minimum human interventions and cycle time
   - Automate material handling, clamping, machining and inspection.
9. **Safety and Ergonomics (Human Engineering)**
   - Use interlocks and sensors to prevent unsafe operation.
   - Provide proper lighting and visibility.
   - Keep controls at a comfortable and accessible height.
   - Reduce excessive noise and vibration.
   - Follow applicable machine-safety standards.

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- **Risk Assessment**: Generally ISO 12100, ANSI B11, OSHA 1910.147 ae the risk assessment standards
- **Guarding & Interlocks**: Mechanical and electronic safeguards i.e. Guarding and safety curtains.
- **Ergonomic Design**: ISO 6385 principles provided that operator comfort and accessibility
- **HMI Standards**: Multilingual touchscreens, intuitive interfaces

10. **Maintainability (Minimum Down time - Performance parameter)**
    - Ensure easy access to components.
    - Provide easy access for **maintenance and inspection**.
    - Simplify lubrication, inspection and replacement.
    - Design for minimum downtime.
11. **Cost-effectiveness (Economic Parameter)**
    - Optimize machine cost against productivity and expected production volume.
    - Use standard components wherever possible.
    - Consider total life-cycle cost, not only initial cost.
12. **Quality and inspection (QC Parameters)**
    - Integrate sensors, gauges or machine vision where necessary.
    - Enable in-process or post-process inspection.
    - Maintain process capability and consistency.
13. **Energy efficiency (Energy Parameters)**
    - Select efficient motors and drives.
    - Minimize idle running and unnecessary pneumatic/hydraulic consumption.
14. **Modular and flexible design (Design Standards)**
    - Use modular units for future modifications.
    - Allow replacement or addition of tooling and fixtures where require

BLOCKS OF SMP DESIGN

The blocks of SPM design cover the entire SPM machine including mechanical design, Electrical and control operation, Automation and Safety. It also covers the integration of various blocks to make the SPM operational. Following are the basic building blocks for SPM.

1) Mechanical Assembly

It includes structural integrity, material selection, kinematics and ergonomics, wear management for coating and hardening techniques to extend tool life etc.
Following are subpart of assembly:

a) Machine Base / Frame
b) Guideways
c) Jigs and Fixtures
d) Tooling

2) Actuation Systems

It handles Hydraulic, pneumatic, servo, or electric actuators depending on force, speed, and precision requirements

a) Pneumatic / Hydraulic System
b) Electric Actuator Assembly
c) Electromechanical Actuation

3) Electrical Assembly

The function is to fulfill the entire electrical requirement to the SPM system. It has a control panel designed to provide electrical connectivity to the entire system.

a) Power System
b) Control Panel
c) PLC and Drives
d) Control System
e) Sensors and Feedback Devices

4) Automation and Safety

Here the function cover under these blocks includes Integrated automation with interlocks, guarding, and safety systems compliant meeting the industrial standards.

a) PLC & HMI Integration

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b) Sensor Networks: Particularly Diagnostics, feedback and predictive maintenance
c) Motion Control: Servo systems, stepper motors and linear actuators.
d) Smart Connectivity: OPC UA, MQTT, Modbus TCP
e) Error Correction and Control

5) AI Powered SPM:

AI-Powered Machines boost the automation in SPMs to make them more user-friendly, accurate, optimised, predict failures and automated decision making.

Modules includes

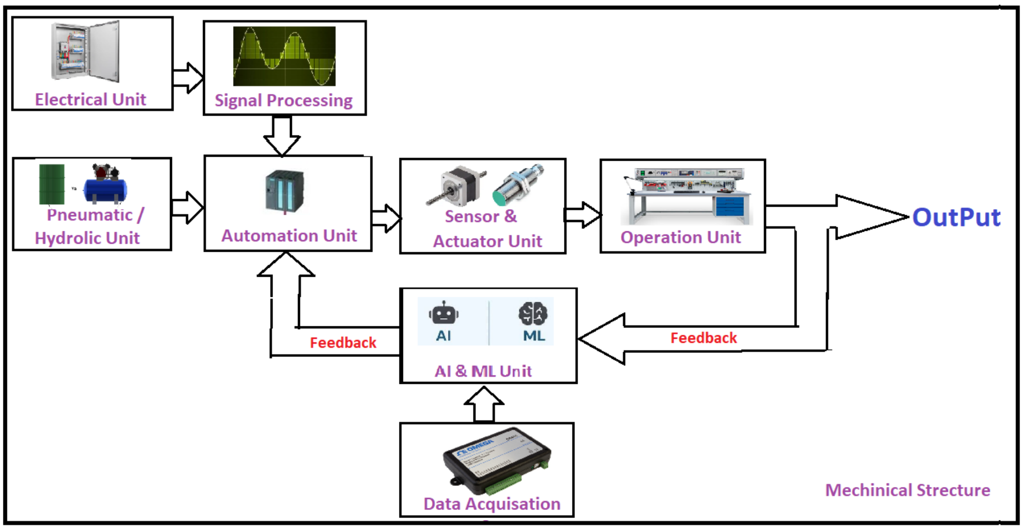
- Defect detection using computer vision
- Predictive maintenance
- Automatic parameter adjustment
- Quality inspection
- Process monitoring
- Fault detection and diagnosis

6) **SPM compliance**

SPM compliance means ensuring that a Special Purpose Machine is designed, manufactured, and operated according to the required safety standards, regulations, specifications, and quality requirements.

- CE Marking (Europe)
- UL Certification (USA)
- CCC Compliance (China)

BLOCK DIAGRAM



Blocks of SMP Design

PHASES OF SMP DESIGN AND DEVELOPMENT

Research -> Feasibility Study -> Project Management -> QC -> Testing and Commissioning

1.Requirement Analysis and feasibility study
2.Process Planning
3.Concept development
4.Detailed mechanical and automation design
5.Manufacturing and assembly
6.PLC programming and system integration
7.Installation, commissioning, and support

MATHEMATICAL ANALYSIS OF SPM

1. Kinematic analysis

Determine the position, velocity and acceleration of each moving component.

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For a linear actuator:

$$v=dtdx \quad a=dt2d2x$$

For rotary motion:

$$\omega=dtd\theta \quad \alpha=dt2d2\theta$$

These equations help determine actuator speed, acceleration and positioning requirements.

In short:

Kinematic Analysis=Position + Velocity + Acceleration + Motion Sequence

It ensures that every moving element of the SPM follows the **required path, speed, and timing** accurately.

2. Cutting-force analysis

For machining operations, cutting force can be estimated from:

$$Fc=KcA$$

where:

- Fc = cutting force
- Kc = specific cutting force
- A = undeformed chip cross-sectional area

For milling:

$$Pc=FcVc$$

where Pc is cutting power and Vc is cutting velocity.

In short:

Proper cutting-force analysis → correct motor + spindle + fixture + structure selection

This helps achieve high accuracy, longer tool life, reduced vibration, and reliable SPM operation.

3. Spindle-power calculation

Spindle power can be calculated from:

$$P=602\pi NT$$

where:

- P = power in watts
- N = spindle speed in rpm
- T = spindle torque in N·m

Required motor power can then be selected by considering efficiency and safety factor.

$$Pm=\eta P\times SF$$

4. Feed-rate calculation

For milling:

$$Vf = fz \times Z \times N$$

where:

- Vf = feed rate
- fz = feed per tooth
- Z = number of teeth
- N = spindle speed

For drilling:

$$Tm = f \times N \times L$$

where:

- Tm = machining time
- L = drilling length
- f = feed/rev
- N = spindle speed.

In an AI-powered SPM, feed rate can be adjusted using real-time data from force, vibration, spindle-load, and tool-wear sensors to optimize the machining process.

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5. Cycle-time mathematical model

For an automated SPM:

$$T_c = T_{load} + T_{position} + T_{machine} + T_{inspect} + T_{unload}$$

If operations are performed simultaneously, the cycle time can be approximated by:

$$T_c = T_{load} + \max(T_1, T_2, \ldots, T_n) + T_{unload}$$

This is particularly useful for demonstrating the productivity advantage of an SPM.

AI can analyse sensor data, tool wear, vibration, spindle load, and production history to optimize feed rate, speed, tool paths, and operation sequencing.

Key relationship

Lower Cycle Time→Higher Production Rate→Higher Productivity

Thus, cycle-time modelling is essential for SPM design, capacity planning, cost estimation, and AI-based optimization.

6. Structural analysis

Machine-frame deformation can be represented by:

$$\Delta = 3E \text{ x } I \text{ x } F \text{ x } L \text{ x } 3$$

for a simplified cantilever model.

Where:

- F = applied force
- L = structural length
- E = Young's modulus
- I = second moment of area.

The design objective is generally:

$$\Delta \leq \delta_{allowable}$$

The AI system can detect abnormal vibration or deformation patterns and provide early warnings of structural problems.

Key objective

High Stiffness + Low Deflection + Low Vibration + Adequate Strength

A properly designed structure ensures that the SPM maintains accuracy, stability, productivity, and long service life.

7. Stiffness analysis

Machine stiffness can be expressed as:

$$K = \delta F$$

Higher stiffness generally helps reduce machining errors and vibration.

For research, you can compare:

$$K_{proposed} > K_{existing}$$

if your proposed structure is actually demonstrated to be stiffer.

8. Vibration analysis

A simplified SPM structural model can be represented as a mass-spring-damper system:

$$m\ddot{x} + c\dot{x} + kx = F(t)$$

Natural frequency:

$$\omega n = mk$$

And:

$$fn = 2\pi 1mk$$

This analysis is useful for avoiding resonance during machining.

9. Servo/ball-screw analysis

For a ball-screw-driven axis:

$$v = 60 \text{ X } p \text{ X } N$$

where:

- p = screw lead
- N = rotational speed.

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Required torque can approximately be calculated from:

$$\mathbf{T=2\pi\eta Fp}$$

where:

- F = required linear force
- p = screw lead
- η = ball-screw efficiency.

10. Fixture-force analysis

The clamping force should be sufficient to resist machining forces.

A simplified condition is:

$$\mathbf{Fclamp\mu \geq SF \times Fcut}$$

where:

- Fclamp = clamping force
- μ = coefficient of friction
- Fcut = machining force
- SF = safety factor.

The actual fixture design should also account for locating geometry, moment loads and workpiece deformation.

11. Tolerance-stack analysis

For a simple worst-case tolerance stack:

$$\mathbf{Ttotal = T1+T2+T3+\cdots+Tn}$$

For statistical RSS tolerance:

T $$\mathbf{RSS = T12+T22+\cdots+Tn2}$$

This can be used to predict the final dimensional accuracy of the SPM.

12. Productivity analysis

Production rate can be estimated as:

$$\mathbf{Q=Tc60}$$

where Q is components/hour if Tc is in minutes.

For example, if:

Tc=2 min/component

then:

Q=260=30 components/hour

13. OEE analysis

For an industrial SPM, Overall Equipment Effectiveness can be calculated as:

$$\mathbf{OEE=A\times P\times Q}$$

where:

- A = Availability
- P = Performance
- Q = Quality.

This gives your research a strong **industrial-performance metric**.

14. Energy analysis

Energy consumption per component:

$$\mathbf{Ec=NcEtotal}$$

where:

- Ec = energy/component
- Etotal = total energy consumed
- Nc = components produced.

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You can compare conventional and proposed SPMs using this parameter.

OPTIMIZATION FOR SPM

To achieve the optimisation i.e to improve the machine's performance so that we can have higher productivity, better quality, lower cost, and minimum downtime.

For an AI-powered SPM, the most important optimization feature is the closed-loop feedback system, where real-time machine data is analyzed and used to improve machine operation continuously.

$$\mathbf{Min\ F(X)= w1Tc + w2C + w3E + w4\delta + w5R}$$

where:

- Tc = cycle time
- C = manufacturing/operating cost
- E = energy consumption
- δ = deformation/error
- R = rejection or reliability-related penalty
- wi = weighting factors
- X = design variables.

Possible design variables

X=[N,f,d,F,L,p,k,…]

representing parameters such as spindle speed, feed, cutting depth, force, dimensions, screw lead and stiffness.

ECONOMICS FOR SPM

A Special Purpose Machine (SPM) is a machine designed to perform a specific operation or a limited number of operations efficiently and automatically. The economics of using an SPM mainly depends on whether the higher initial investment is justified by the lower production cost and higher productivity. The economic analysis of an SPM determines whether the investment in a dedicated machine is financially justified compared with conventional/general-purpose machines.

1. Initial Investment Cost

The initial SPM cost can include:

$$\mathbf{CI = CM + CT + CF + CA + CI}$$

where:

- CM = machine/structure cost
- CT = tooling cost
- CF = fixture cost
- CA = automation/control cost
- CI = inspection/integration cost

Typical components include:

- Machine frame
- Spindle and motors
- Servo drives
- PLC/HMI
- Fixtures
- Tooling
- Sensors
- Pneumatic/hydraulic systems
- Safety systems
- Installation and commissioning

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2. Operating Cost
To estimate Annual operating cost we can have:

$$CO = CL + CE + CM + CT + CC$$

where:

- CL = labour cost
- CE = energy cost
- CM = maintenance cost
- CT = tooling cost
- CC = consumable cost

3. Cost per Component

One of the most important SPM economic parameters is:

$$Cpc= Cannual / Nannual$$

where:

- Cpc = production cost per component
- Cannual = total annual production cost
- Nannual = annual production quantity.

For high-volume production, an SPM can reduce cost/component because the higher capital investment is distributed over a large production volume.

4. Cycle-Time Economics

Suppose:
Conventional machine:

$$Tc=5 \text{ min/component}$$

SPM:

$$Tc=2 \text{ min/component}$$

Production capacity increases from:

$$Q=560=12 \text{ components/hour}$$

To:

$$Q=260=30 \text{ components/hour}$$

This increased throughput is a major economic advantage of SPMs.

5. Labour Cost Saving

If automation reduces operator involvement:

$$SL= CL, old−CL,new$$

where SL is annual labour-cost saving.
However, the economic analysis should consider operator redeployment, supervision and maintenance requirements rather than assuming labour becomes zero.

6. Tooling Cost

Tool consumption can be calculated as:

$$CT = NT \times Ctool$$

where:

- NT = number of tools consumed
- Ctool = cost per tool.

Longer tool life reduces the production cost.

7. Energy Cost
Energy cost per component:

$$CE = NP \times t \times CkWh$$

where:

- P = machine power
- t = operating time
- CkWh = electricity price
- N = components produced.

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A more meaningful comparison is often kWh/component, rather than machine rated power alone.

8. Break-Even Point

The break-even production quantity can be estimated as:

QBE = CGPM − CSPMF

where:

- F = additional fixed investment in SPM
- CGPM = variable cost/component using general-purpose equipment
- CSPM = variable cost/component using SPM.

This tells you how many components must be produced before the SPM becomes economically advantageous.

9. Payback Period

The **Payback Period** is the time required to recover the **initial investment** made for a Special Purpose Machine (SPM) through the savings or additional profit generated by the machine.

Formula

Payback Period = Initial Investment / Annual Cash Savings

Where:

- **Initial Investment** = Cost of SPM − any applicable existing-equipment value
- **Annual Cash Savings** = Annual operating cost savings or additional annual profit

Example

Suppose:

- Cost of SPM = ₹20,00,000
- Annual savings = ₹5,00,000

Then:

Payback Period = 5,00,000 / 20,00,000

Payback Period = 4 years

So, the SPM will recover its initial investment in approximately **4 years**.

10. Return on Investment (ROI)

ROI = (Annual Net Benefit / Initial Investment) ×100

A higher ROI generally indicates a more attractive investment, subject to the company's required return and risk.

Example

Suppose:

- Initial SPM investment = ₹20,00,000
- Annual savings = ₹6,00,000
- Additional annual operating/maintenance cost = ₹1,00,000

Net annual return:

=6,00,000−1,00,000 =₹5,00,000

Therefore:

ROI = (20,00,000 / 5,00,000)×100

ROI=25%

11. Total Cost of Ownership

For research, a better approach is to consider Life-Cycle Cost (LCC):

LCC = Cinitial + Coperation + Cmaintenance + Cenergy + Cdowntime − Cresidual

This is more comprehensive than comparing only the purchase price.

In short:

TCO=All Lifetime Costs−Residual Value

TCO gives a more realistic economic comparison between an AI-powered SPM and a conventional machine.

TESTING, VALIDATION, AND GLOBAL COMMISSIONING

This stage is very crucial and critical. These stages are especially important because the machine is highly customized, and problems discovered after installation at the customer's site can be very expensive to correct. It generally refers to the final stages before handing the machine over for production.

Testing : Testing checks whether the SPM operates correctly according to its design and standards.

The check points are: Mechanical movement and alignment, Electrical and control-system operation, Hydraulic/pneumatic systems, Sensors, switches, and safety devices, Machine cycle time, Tool and fixture operation, Repeatability and accuracy, Emergency-stop and safety functions

Validation: Validation confirms that the machine actually meets the customer's production requirement and specifications
The check points are:Required production rate, Component dimensional accuracy, Product quality, Cycle time Repeatability, Rejection rate, Reliability, Safety requirements

Global Commissioning: Global commissioning is the process of installing, starting up, testing, and accepting the SPM at the customer's actual production site, often in another country.
The check points are:: Transportation and installation, Machine levelling and alignment, Electrical/pneumatic/hydraulic connections, Software and control-system setup, Final production trials, Operator training, Troubleshooting, Customer acceptance, Documentation and handover

IMPORTANT STANDARDS FOR SPM DESIGN

For an internationally oriented research/project specification, commonly relevant standards include:

- ISO 12100 – Safety of machinery; risk assessment and risk reduction
- ISO 13849-1 – Safety-related parts of control systems
- IEC 60204-1 – Electrical equipment of machines
- ISO 14120 – Guards and protective devices
- ISO 13850 – Emergency-stop function
- ISO 14119 – Interlocking devices associated with guards
- ISO 13857 – Safety distances to prevent access to hazardous zones
- ISO 4413 – Hydraulic fluid power safety
- ISO 4414 – Pneumatic fluid power safety

The exact standards applicable depend on the machine type, country, intended use, and integration with other equipment.

CONCLUSION

The main criticism of an SPM is therefore high investment and low flexibility in exchange for high productivity and consistent quality whereas on contrarious SPM are future of Industries however the overall Designing Special Purpose Machines i.e. SPM is a multidisciplinary challenge where mechanical design, automation, ergonomics, and digital intelligence converge. For industries SPM hopes to keep pace with the economy it can add value for savings, higher productivity, reduced cycle time, lower handling/labour cost and improved quality are sufficient to recover its higher initial investment within an acceptable payback period. By embracing a holistic, globally aware design approach, engineers can create SPM that not only meet technical specifications and industry standards but also empower manufacturers to scale efficiently, safely, and sustainably anywhere in the world.

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