

Supplementary Materials

Development and Implementation of a Smart Single-Station Manual Assembly Cell for an Inexperienced Worker to Enhance Industrial Efficiency in an MSME

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Table S1 Dimensions of SAT.

Component	Dimensions
Assembly table	L=70 cm, H=171 cm, W=58.5 cm
Workspace	70 cm x 58.2 cm
Control panel	H=30.5 cm, L=62.2 cm, W=21 cm
Leg movement space	25 cm x 21 cm
Bin sensor position (Customizable up to three levels with each level having maximum capacity of seven bins)	Along length, L=70 cm, First level, H=26.7 cm

Table S2 Actual cycle time recorded for twenty assembly cycles by each of five workers with Traditional and Smart SSMAC.

Worker	1	2	3	4	5	1	2	3	4	5
Cycle No.	Cycle time for Traditional SSMAC (s)					Cycle time for Smart SSMAC (s)				
1	1252	1274	1291	1236	1198	936	971	922	929	926
2	1211	1260	1281	1230	1191	929	965	919	925	922
3	1206	1258	1269	1226	1182	928	957	917	923	918
4	1197	1252	1259	1225	1177	924	954	915	922	915
5	1192	1243	1256	1215	1161	922	948	914	921	912
6	1172	1242	1249	1210	1158	916	945	913	919	909
7	1165	1236	1246	1207	1155	911	944	912	918	906
8	1146	1225	1243	1201	1149	908	940	911	915	905
9	1145	1218	1241	1185	1148	907	937	910	914	903
10	1143	1205	1231	1168	1138	900	930	909	913	901
11	1137	1199	1228	1147	1135	899	924	907	912	898
12	1134	1193	1209	1139	1132	898	919	906	908	897
13	1128	1183	1197	1138	1129	895	917	904	906	892
14	1128	1180	1193	1134	1128	892	915	901	904	890
15	1126	1179	1190	1122	1127	891	913	898	895	888
16	1111	1177	1184	1119	1122	889	911	896	890	884
17	1105	1167	1182	1116	1115	887	910	894	887	881
18	1098	1161	1178	1115	1108	883	908	892	886	877
19	1092	1155	1177	1114	1102	882	907	891	883	874
20	1084	1153	1172	1112	1098	876	904	890	882	873
Total	22972	24160	24476	23359	22853	18073	18619	18121	18152	17971
Grand Total	117820					90396				

Table S3 Data analysis for assembly cycles with Traditional SSMAC: Standard Time Determination.

Worker	Actual cycle time (s)		Total time required to complete 20 cycles (s)	Average cycle time (s)	Assessment of worker's speed as of standard pace (%)	Standard Time (s)
	Minimum	Maximum				
1	1084	1252	22972	1148.60	95 (Slower than standard pace)	1200.29
2	1153	1274	24160	1208.00	90 (Slower than standard pace)	1195.92
3	1172	1291	24476	1223.80	90 (Slower than standard pace)	1211.56
4	1112	1236	23359	1167.95	93 (Slower than standard pace)	1194.81
5	1098	1198	22853	1142.65	95 (Slower than standard pace)	1194.07
Overall for 100 cycles			117820	1178.20	Average Standard Time	1200

Table S4 Data analysis for assembly cycles with Smart SSMAC: Standard Time Determination.

Worker	Actual cycle time (s)		Total time required to complete 20 cycles (s)	Average cycle time (s)	Assessment of worker's speed as of standard pace (%)	Standard Time (s)
	Minimum	Maximum				
1	876	936	18073	903.65	95 (Slower than standard pace)	944.31
2	904	971	18619	930.95	90 (Slower than standard pace)	921.64
3	890	922	18121	906.05	95 (Slower than standard pace)	946.82
4	882	929	18152	907.60	90 (Slower than standard pace)	898.52
5	873	926	17971	898.55	95 (Slower than standard pace)	938.98
Overall for 100 cycles			90396	903.96	Average Standard Time	930

Statistical power analysis (planning and post-hoc)

To justify the experimental sample size and quantify the study's sensitivity to detect differences between Traditional and Smart SSMAC, authors performed both a planning-style sample-size calculation for a range of assumed effect sizes and a post-hoc power analysis using the observed per-worker standard times (Tables S3 and S4).

1. Planning/sample-size calculation (paired comparison)

For a paired-sample test the required sample size n (number of subjects) for a desired two-tailed significance level α and power $1-\beta$ can be approximated using:

$$n \approx \left(\frac{Z_{1-\alpha/2} + Z_{1-\beta}}{d} \right)^2$$

where d is the Cohen's d for paired data (standardized mean difference), and Z are standard normal quantiles. Using $\alpha = 0.05$ (two-tailed) and a common power target $1-\beta = 0.80$ ($Z_{1-\alpha/2} = 1.96$, $Z_{1-\beta} = 0.842$), the constant $(Z_{1-\alpha/2} + Z_{1-\beta})^2 = 7.851$. Table S5 shows sample size needs for representative effect sizes.

Table S5 Required sample size (paired test) for various Cohen's d .

Assumed Cohen's d (paired)	Required subject n (rounded up)
0.20 (small)	197
0.50 (medium)	32
0.80 (large)	13
1 (very large)	8
1.50 (very large)	4

This shows that, for a medium effect ($d = 0.5$), ~32 participants would be required to reach 80% power; for very large effects ($d \geq 1.5$), far fewer subjects are needed.

2. Post-hoc analysis using observed data (per-worker standard times)

Authors computed the paired differences in Standard Time per worker (Traditional – Smart) using the five worker-level values shown in Tables S3 and S4:

- Traditional standard times (s): 1200.29, 1195.92, 1211.56, 1194.81, 1194.07
- Smart standard times (s): 944.31, 921.64, 946.82, 898.52, 938.98

From these 5 paired observations authors obtained:

- Mean difference $\bar{D} = 269.276$ s
- Sample standard deviation of differences $s_D = 16.981$ s
- Paired Cohen's $d = (\bar{D}/s_D) = 15.86$ (very large effect)
- Paired t-statistic: $t = [\bar{D}/(s_D / \sqrt{n})] = 35.46$ with $df = 4$

- Two-tailed $p \approx 3.78 \times 10^{-6} < 0.0001$, by conventional criteria, the difference between the means is considered to be extremely statistically significant.

Using this observed effect size ($d \approx 15.86$) and $n = 5$, the achieved power is effectively 100% (i.e., the observed difference is extremely large and highly significant at conventional α levels).

Interpretation and caveats:

- The **planning** calculations show that a conventional planning assumption of *medium* effect ($d = 0.5$) would require many more participants (~32) to achieve 80% power.
- The **post-hoc** result demonstrates that at the *worker-average* level the observed effect is extremely large and easily detectable with five workers (hence the high significance). The large observed Cohen's d arises because the difference in standard times between Traditional and Smart SSMAC is large (~269 s) while the between-worker variability of those worker-average differences is small (~17 s).
- **Caution:** the post-hoc power is conditional on the observed effect and the aggregation level used (worker average). It should not be taken to imply that $n = 5$ is sufficient for all possible products, operators, or finer-grained (per-cycle) analyses. For broader generalization, future studies should include more operators, multiple product types, and hierarchical analyses (cycles nested within operators).

Table S6 Data recorded pertaining to errors, instances of delayed cycle time and defective products for assembly cycles with Traditional SSMAC.

Worker	Number of operator errors recorded	Number of instances of delayed cycle time	Number of instances of adherence to the set cycle time	Number of defective products (Nok Parts)
1	4	3	17	3
2	2	10	10	1
3	1	12	8	0
4	3	8	12	2
5	4	0	20	4
Total	14	33	67	10

Table S7 Data recorded pertaining to errors, instances of delayed cycle time and defective products for assembly cycles with Smart SSMAC.

Worker	Number of operator errors recorded	Number of instances of delayed cycle time	Number of instances of adherence to the set cycle time	Number of defective products (Nok Parts)
1	1	1	19	1
2	0	9	11	0
3	1	0	20	1
4	0	0	20	0
5	2	0	20	1
Total	4	10	90	3

Table S8 Performance metrics indicating better performance by Smart SSMAC over Traditional.

Performance Metric	Details
Reduction in Target/Set Standard Cycle Time	$= ((1200 - 930) / 930) \times 100$ $= 22.50\%$
Improvement in Total time required to complete 100 cycles	$= ((117820 - 90396) / 117820) \times 100$ $= 3.28\%$
Decrease in Number of operator errors recorded	$= ((14 - 4) / 14) \times 100$ $= 71.43\%$
Decrease in number of instances of delayed cycle time	$= ((33 - 10) / 33) \times 100$ $= 69.69\%$
Improvement in the number of instances of adherence to the set cycle time	$= ((90 - 67) / 67) \times 100$ $= 34.33\%$
Decrease in defect rate	$= ((10 - 3) / 10) \times 100$ $= 70.00\%$

Table S9 Comparison of reasons for production of final defective assembled product (Nok Parts)

Reason for defective products	Traditional SSMAC	Smart SSMAC
Software or System errors		
Malfunctioning sensors	Not Applicable	✓ (Newly Introduced)
Software glitches or bugs	Not Applicable	✓ (Newly Introduced)
Incorrect programming/configuration	Not Applicable	✓ (Newly Introduced)
Human error		
Incorrect part selection	✓	✗
Incorrect part placement	✓	✗
Failure to follow digital instructions	Not Applicable	✓
Inattention to real-time feedback	Not Applicable	✓
Ignoring manual quality checks	✓	✓
Misinterpretation of assembly instructions	✓	✗
Fatigue and lack of concentration	✓	✗
Inconsistent skill levels		
Variations in skill levels among operators	✓	✓
Lack of proper training and experience	✓	✓
Manual measurement errors		
Inaccurate measurements during assembly	✓	✓
Failure to maintain consistent tolerances	✓	✓
Inadequate training on smart systems		
Failure to intervene during system malfunctions	✓	✓
Operators not fully trained on new systems	✓	✓
Misunderstanding of digital tools and interfaces	Not Applicable	✓
Power or connectivity issues		
System shutdown due to power failure	Not Applicable	✓ (Newly Introduced)
Loss of connectivity in network-dependent systems	Not Applicable	✓ (Newly Introduced)
Improper tool usage (Despite smart tools)		
Failure to use tools correctly even with assistance	✓	✗
Ignoring tool feedback and warnings	✓	✗
Incorrect selection of tools	✓	✗
Incorrect tool settings	✓	✗
Material handling issues		
Mishandling of components	✓	✗
Incorrect part placement due to manual intervention	✓	✗
Misplacement or mix-up of parts	✓	✗
Environmental factors		
Disruptions or distractions in the work environment	✓	✓
Lighting or ergonomic issues affecting the operator	✓	✓
Inconsistent assembly process		
Variability in assembly procedures	✓	✗
Differences in the sequence of assembly steps	✓	✗
Complex assembly requirements		
Assembly of intricate or highly detailed components	✓	✗
Challenges with unusual or custom assembly tasks	✓	✗

Table S9 Comparison of reasons for production of final defective assembled product (Nok Parts) (cont.)

Reason for defective products	Traditional SSMAC	Smart SSMAC
Lack of documentation		
Absence of standardized assembly procedures	✓	✗
Outdated or incorrect assembly instructions	✓	✗
Inadequate quality control		
Lack of real-time feedback on quality	Not Applicable	✓
Limited immediate quality checks	✓	✗

Table S10 Economic analysis for Traditional and Smart SSMAC based on one hundred cycles.

Sr. No.	Description	Equation	Traditional SSMAC	Smart SSMAC	Remark
1	Hourly labor rate in INR for novice or inexperienced worker		75	75	
2	Cycle time per assembled product in seconds		1200	930	22.5% ↓
3	Average number of assembly cycles that can be completed in an hour or Average number of products assembled in an hour or Number of units assembled per hour	= 3600 / cycle time (s)	3	3.87	29% ↑
4	Average labor cost per unit (i.e. one assembly cycle) in INR (Overall production including defective product cycles)	= Hourly labor rate in INR / Average number of products assembled (number of assembly cycles) in an hour	25	19.38	22.5% ↓
5	Total defective products recorded over 100 assembly cycles		10	3	70% ↓
6	Defect rate (%)	= (total defective products recorded / total no. of assembly cycles) x 100	10	3	70% ↓
7	Number of units to be assembled to produce one hundred good quality products	= [100 / (1 - ((defect rate)/100))]	111.11	103.09	7.2% ↓
8	Additional cost of labor to company per defective product in INR	= 4 [@] × Average labor cost per unit (i.e. one assembly cycle) in INR (Overall production including defective product cycles)	100	77.52	

Table S10 Economic analysis for Traditional and Smart SSMAC based on one hundred cycles. (cont.)

Sr. No.	Description	Equation	Traditional SSMAC	Smart SSMAC	Remark
9	Total labor cost of defective product in INR	= Total defective products recorded over 100 assembly cycles × Cost of labor to company per defective product in INR	750	174.42	76.7%↓
10	Assembly labor cost in INR Associated with production of one hundred good quality products	= [Average Labor cost per unit in INR (Overall production including defective product cycles) × 100] + Total labor cost of defective product in INR	3250	2112.42	35% ↓
11	Cost of labor saved in INR with production of one hundred good quality products				= 3250 - 2112.42 = 1137.58
12	Average labor cost per unit in INR (for Good quality/Acceptable production)	= Assembly labor cost in INR associated with production of one hundred good quality products / 100	32.50	21.1242	35% ↓
13	Labor cost saving per unit in INR (for Good quality/Acceptable production)				= 32.50 - 21.12 = 11.38
14	% Labor cost saving per unit in INR (for Good quality/Acceptable production)	= {[Cost saving per unit in INR (for Good quality/Acceptable production)] / Average Labor cost per unit in INR (for Good quality/Acceptable production) for traditional SSMAC} × 100			= (11.38 / 32.50) × 100 = 35% ↑

@The cost is computed considering that the defective assembled product is an outcome of improper assembly (may be due to tolerance stacking/material defects/improper fixturing and clamping/batch variation).

The defective (Nok) assembled product can be further disassembled and reassembled with interchangeable parts. While disassembling, suitability of each child is checked for further reassembly. Replacement of any defective/damaged child part during reassembly incurred respective extra cost. Thus, the minimum cost includes further steps: (i) assembly cycle, (ii) disassembly cycle, (iii) child part

inspection for every part, (iv) replacement of defective child part, if any, (v) reassembly with interchangeable child parts by selecting minimum 50% of respective different child parts other than the earlier defective (Nok) assembly. If there is no any quality issue with each of the child part of the earlier disassembled defective (Nok) assembly, then 50% of the concerned non utilized child parts are randomly distributed to their respective bins and it is ensured that they do not get assembled together in any further assembly cycle for a particular assembled product.

Additional cost of labor to company per defective product is calculated by considering that defects in the assembled product occur due to improper assembly. This may happen because of tolerance stacking, material defects, incorrect fixturing and clamping, or batch variations.

These causes are common for both the environments, traditional as well as smart SSMAC. However, the causes for the reduction in defect rate due to smart over traditional SSMAC are already discussed separately in Table 8. If a defective (Nok) product is found, it can be disassembled and reassembled using interchangeable parts. During disassembly, each child part is checked for suitability for reassembly. If any child part is found defective or damaged, it is replaced, leading to additional costs.

The minimum cost includes the following steps:

1. Assembly cycle
2. Disassembly cycle
3. Inspection of each child part
4. Replacement of any defective child part
5. Reassembly using interchangeable child parts, ensuring that at least 50% of the parts are different from those used in the previous defective (Nok) assembly.

Distribution cycle. Out of the total child parts, from the disassembled defective (Nok) assembly that meet quality standards, 50% of the unused child parts are randomly placed back into their respective bins. It is to be ensured that these parts are not used together again in any future assembly of the same product or different product with soft variety.

Table S11 Comparative Analysis: Traditional SSMAC vs. Smart SSMAC.

Performance Metric	Traditional SSMAC	Smart	Remark
Standard Cycle Time	1200 s	930 s	22.50% ↓
Number of operator errors recorded i.e. Error Rate	14	4	71.43% ↓
Instances of delayed cycle time	33	10	69.69% ↓
Instances of adherence to the set cycle time	90	67	34.33% ↓
No. of defects i.e. Defect rate	10	3	70.00% ↓
Labour Cost Per Unit in INR	32.50	21.12	35.00% ↓