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Engineering Design and Ergonomic Evaluation of an Assistive Device for Manual Material Handling

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***Abstract* — Manual material handling (MMH) remains a major contributor to work-related musculoskeletal disorders in manufacturing environments. This study proposes and evaluates an assistive device for box panel handling aimed at reducing ergonomic risk during lifting and transport operations at PT. XYZ. A case-study approach was employed using multiple ergonomic assessment methods, including the Nordic Body Map (NBM), Rapid Entire Body Assessment (REBA), the Revised NIOSH Lifting Equation (RNLE), and the Snook Tables. Baseline results indicated dominant lower-back (77%) and upper-back (71%) complaints, a high-risk REBA score of 12, low recommended weight limits (4.46–4.91 kg), and excessive lifting indices (5.50–6.05) for a maximum load of 37 kg. The Snook analysis yielded a maximum acceptable weight of 13.0 kg with a load-to-MAW ratio of 1.38. A trolley-based assistive device integrating lifting and transfer support was then designed to minimize trunk flexion and eliminate manual carrying during transport. Post-intervention evaluation showed substantial improvements, with the REBA score reduced to 1, lifting indices below unity, and the load-to-MAW ratio approaching zero. These results demonstrate that engineering controls in the form of practical assistive devices can effectively reduce ergonomic risk and improve manual material handling safety in industrial settings.**

***Keywords:* Assistive Device, Ergonomic Risk Assessment, Manual Material Handling, Revised NIOSH Lifting Equation.**

I. INTRODUCTION

Manual material handling (MMH) remains a major contributor to work-related musculoskeletal disorders (WMSDs) in manufacturing and logistics operations [1]-[6]. Repetitive lifting, carrying, and load transport impose cumulative biomechanical demands—particularly on the trunk and shoulder regions—leading to fatigue and chronic musculoskeletal symptoms [7], [8]. Empirical studies also report that manual handling–dominant work frequently exhibits elevated discomfort and postural risk when assessed using standardized symptom screening and observational posture methods [9].

PT. XYZ, a medium-scale manufacturer of electrical panel components, currently relies on manual lifting and transportation of box panels weighing 18–37 kg over a 22.5 m route, repeated up to 70 cycles per day. Baseline screening using a Nordic Body Map (NBM) approach indicated substantial discomfort concentrated in the lower back [10]. Postural assessment using Rapid Entire Body Assessment (REBA) produced a score of 12, indicating a high-risk posture requiring prompt corrective action [11]. Biomechanical evaluation using the Revised NIOSH Lifting Equation (RNLE) reported lifting index values exceeding the recommended safe threshold (LI > 1.0), suggesting elevated low-back injury risk under the observed task conditions [12], [13]. Furthermore, psychophysical evaluation using the Snook and Ciriello Tables estimated a maximum acceptable weight (MAW) of approximately 12–13 kg for comparable handling conditions, which is far below the current load demands [14]. Collectively, these results confirm a clear mismatch between task requirements and human capability in the existing process.

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Occupational safety and health (OSH) frameworks emphasize that risk reduction is most effective when hazards are controlled at the source, prioritizing engineering controls over administrative measures and personal protective equipment [15]-[17]. Applied OHS studies further show that combining ergonomic identification with structured risk assessment supports more practical and defensible workplace improvements [18], [19].

However, many medium-scale industries still face barriers to adopting engineered solutions due to cost constraints and limited technical resources, and ergonomic risk identification often fails to translate into implementable device concepts [20]. Therefore, this study develops a practical material handling aid as an engineering control to reduce physical workload and ergonomic risk during box panel transfer at PT. XYZ. The contribution lies in linking quantitative ergonomic diagnosis to an actionable technical redesign and evaluating improvement using standard ergonomic indicators.

II. METHODS

This study employed an applied industrial engineering case-study approach to reduce ergonomic risks associated with manual material handling (MMH) of box panels at PT. XYZ. The methodology integrates baseline ergonomic risk assessment with a rational engineering design process based on Nigel Cross to generate, evaluate, and finalize a practical material handling aid.

A. Study Setting, Participants, and Task Observation

PT. XYZ is a medium-scale manufacturer of electrical panel components. The MMH process under study involves repetitive lifting, transporting, and placing box panels from the packing area to the truck loading point. The company employs 35 workers, all of whom are users involved in the box panel handling process. Field observations were conducted on representative task cycles covering (i) lifting at the origin point, (ii) transport along the packing-to-truck route, and (iii) placement at the destination.

Work measurement captured parameters required for ergonomic analysis and design requirement definition, including load weight range, box panel dimensions, horizontal and vertical load locations, vertical travel distance, asymmetry conditions, coupling quality, handling frequency/duration, carrying distance, route width/length, and truck bed height.

B. Baseline Ergonomic Risk Assessment Methods

Four complementary ergonomic assessment methods were applied to quantify baseline risk and justify the need for engineering redesign.

1) *Musculoskeletal symptom assessment*
   A Nordic Body Map (NBM)-based instrument was used to identify the distribution and severity of musculoskeletal discomfort among workers performing MMH tasks [12].
2) *Postural risk assessment*
   Rapid Entire Body Assessment (REBA) was applied to evaluate whole-body postural loading during lifting and transfer activities and to determine the urgency of corrective actions [11].
3) *Biomechanical lifting analysis*
   The Revised NIOSH Lifting Equation (RNLE) was used to compute the Recommended Weight Limit (RWL) and Lifting Index (LI) for the observed lifting task [9], [10]. To improve replicability and reduce manual calculation error, RWL and LI were computed using the ErgoPlus RNLE Calculator by entering task parameters (horizontal/vertical locations, vertical travel distance, asymmetry angle, coupling quality, frequency, and task duration) to obtain RNLE multipliers and final RWL/LI outputs [21].
4) *Psychophysical evaluation*
   The Snook and Ciriello Tables were used to estimate Maximum Acceptable Weight (MAW) under comparable manual handling conditions [8]. In this study, MAW and the external load-to-MAW ratio were obtained using the NexGen Ergonomics (ErgoIntelligent MMH) web-based tool implementing Snook-table-based psychophysical models [22].

C. Needs Identification

Needs identification was performed to ensure traceability from shop-floor constraints and user expectations to measurable engineering requirements. System needs were derived from

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workplace measurements and workflow constraints (e.g., box panel weight and dimension range, route constraints, and truck interface height). User needs were collected using an open-ended questionnaire administered to all 35 workers. The responses were compiled and thematically grouped into five dominant criteria that emerged repeatedly: comfort and usability, safety and health, effectiveness, versatility and durability, and efficiency. This needs-to-requirements structuring aligns with work-system design principles that integrate technical constraints with human-centered considerations [23], [24].

The grouped user needs were then translated into quantitative performance specifications (e.g., minimum load capacity, platform/table sizing, stability during transport, route compatibility, and ergonomic handle interface). These specifications served as the formal design requirements input for the rational design process.

D. Assistive Device Design Method

The proposed material handling aid was developed using the rational design method presented by Nigel Cross, applied in six stages to ensure a transparent progression from needs to final design output [25]:

1) *Clarifying objectives*
   Design objectives were organized hierarchically with the primary objective of reducing MMH ergonomic risk, supported by safety, usability, durability, layout compatibility, and efficiency objectives.
2) *Function Analysis*
   A black-box model defined the transformation from operator input to controlled product transfer, and a transparent-box decomposition translated the overall goal into sub-functions, including load support, controlled movement, stabilization during transport, safe placement at the destination, and operator–device interaction.
3) *Performance Specification*
   Performance specifications were derived by integrating ergonomic diagnosis, system constraints (box geometry, route dimensions, truck bed height), and grouped user needs. Key targets included reducing postural risk, decreasing biomechanical lifting risk, ensuring adequate stability, and meeting efficiency expectations.
4) *Determining Technical Characteristics*
   The technical characteristics of the material handling aid were derived using Quality Function Deployment (QFD). User needs (voice of users) were listed on the “WHATs” side, and engineering characteristics were defined as “HOWs”. The relationship matrix was used to translate each need into measurable technical directions (e.g., frame strength, stability, mobility, interface ergonomics, platform geometry, and maintainability). Importance weights for the WHATs were obtained from the questionnaire responses of the 35 workers, and the resulting weighted priorities were used to identify the critical engineering characteristics that should be emphasized in concept generation and selection.
5) *Generating alternatives*
   Alternative solution principles were generated for each sub-function and combined to form feasible concepts.
6) *Evaluating alternatives*
   Concept selection was performed using a weighted objectives method as recommended in systematic engineering design practice [25], [26]. Criterion weights were derived from normalized mean importance ratings obtained from the 35-user questionnaire. Each concept was scored against each criterion, and a total weighted score was computed to identify the best overall concept.
   To support rational concept evaluation, the relative importance of evaluation criteria was determined before concept selection. A pairwise comparison using the zero–one method was applied to the representative user-need criteria. Each criterion was compared against the others based on perceived importance derived from brainstorming sessions and questionnaire responses involving 35 operators and supervisors. The resulting scores were normalized to obtain criterion weights, which were subsequently used in the weighted objectives method for concept evaluation

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7) *Improving details*

The selected concept was refined through dimensioning, material/component selection, and simplification for manufacturability and maintenance, resulting in a finalized design configuration for implementation.

E. Assistive Device Design Method

The effectiveness of the proposed device was evaluated by comparing baseline vs. redesigned conditions using the same ergonomic indicators: (i) REBA score, (ii) RNLE outputs (RWL and LI), and (iii) Snook-based MAW ratio. Improvement was indicated by reduced postural and biomechanical risk levels and improved psychophysical feasibility, consistent with OSH frameworks emphasizing engineering controls to mitigate risk at the source [15]–[17].

III. RESULT AND DISCUSSION

A. Results of Ergonomic Risk Assessment

1. Musculoskeletal symptoms

The Nordic Body Map screening indicates substantial musculoskeletal complaints after operators perform the MMH task. In particular, the lower back is the dominant complaint region, followed by back discomfort, confirming that the task imposes a high physical burden on the trunk region. The baseline complaint proportions can be referenced from the NBM results reported in the case study documentation.

As shown in Table 1, the highest prevalence of discomfort was reported in the lower back (77%), upper back (71%), and back region (63%), indicating that the MMH task primarily imposes excessive loading on the trunk and spinal regions.

Table 1. Nordic Body Map Questionnaire Summary

No	Complaint	Total	Percentage
1	Lower back pain	27	77%
2	Upper back pain	25	71%
3	Back pain	22	63%
4	Pain in the upper neck	19	54%
5	Pain in the upper right arm	16	46%
6	Shoulder pain	11	31%
7	Pain in the right knee	10	29%
8	Pain in the left knee	10	29%
9	Pain in the right arm	10	29%
10	Pain in the left arm	9	26%
11	Pain in the lower right leg	8	23%
12	Pain in the left wrist	8	23%
13	Pain in the wrist	8	23%
14	Pain in the upper left arm	7	20%
15	Pain in the left ankle	5	14%
16	Pain in the right ankle	5	14%
17	Pain in the left calf	4	11%
18	Pain in the right calf	4	11%
19	Pain in the lower neck	3	9%

2. *Psychophysical Evaluation*

Psychophysical evaluation using the Snook Tables for the transport route from packing to the truck shows that the Maximum Acceptable Weight (MAW) is approximately 18 kg at 0.5 lifts/min, while the observed task requires handling loads beyond that level. The baseline external load-to-MAW ratio is 1.47 (> 1), indicating that the task is hazardous and requires improvement.

Figure 1 presents the Snook Table (psychophysical) evaluation of the packing-to-truck carrying task. The Maximum Acceptable Weight (MAW) is 18.0 kg, and the external load-to-MAW ratio is 1.47 (>1), indicating a high-risk task requiring ergonomic intervention. The output was generated using NexGen Ergonomics software based on the Snook and Ciriello psychophysical guidelines.

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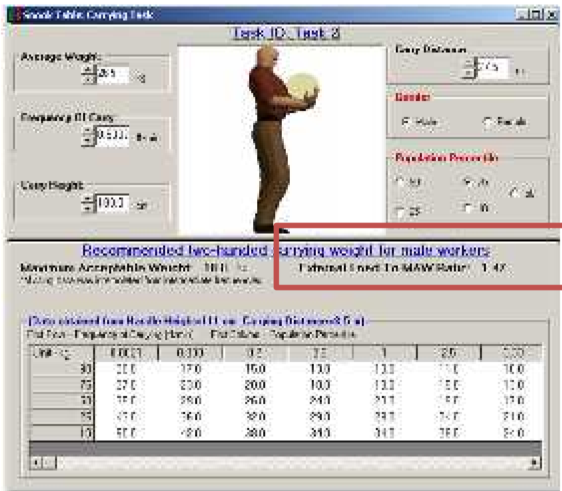

Figure 1. Snook Table Analysis for the Packing-to-Truck Carrying Task

3. Biomechanical Lifting Analysis

The results of the RNLE analysis for the baseline lifting task are presented in Figure 2. The calculated Recommended Weight Limit (RWL) values are 4.46 kg at the origin and 4.91 kg at the destination, which are substantially lower than the actual handled loads.


Figure 2. RNLE results for the baseline lifting task

For the maximum observed load of 37 kg, the corresponding Lifting Index (LI) values reach 6.05 (origin) and 5.50 (destination), indicating a very high-risk lifting condition (LI > 1). These findings confirm that the existing lifting task exceeds acceptable biomechanical limits and requires immediate ergonomic intervention.

4. Postural Risk Assessment

Postural assessment using REBA indicates a high-risk posture during baseline lifting. As shown in Fig. 3, the documented lifting posture involves pronounced trunk flexion and upper-limb deviation, which is reflected in the REBA assessment presented in Fig. 4. The resulting REBA score of 12 corresponds to a high/sustained risk category and requires prompt corrective action.

Figure 3. Baseline lifting posture

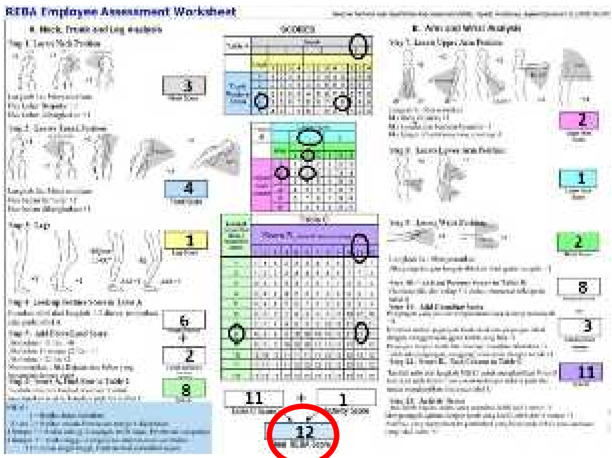

Figure 4. Baseline REBA assessment output

B. Result of Needs Identification

System needs derived from shop-floor observation and measurement indicate that the material handling solution must accommodate box panels weighing up to 37 kg and having maximum dimensions of approximately 80 cm × 60 cm. The device must be operable along the existing transport route (≈15 m length, ≈2 m width), interface safely with the truck bed height (≈145

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cm), and maintain stability during pushing and placement to prevent load shifting.

User needs were collected from all 35 workers involved in the handling process through an open-ended questionnaire and follow-up discussion. Responses were summarized and grouped using thematic analysis, resulting in five dominant need categories: comfort and usability, safety and health, effectiveness, versatility and durability, and efficiency. These categories were subsequently used to formulate representative user needs that guided the development of design specifications and concept evaluation.

The representative user needs are summarized as follows: (i) easy and comfortable operation, (ii) avoidance of awkward postures, (iii) safe handling without injury risk, (iv) reduced musculoskeletal load, (v) ability to handle heavy loads, (vi) smooth transport during transfer, (vii) usability for different materials, (viii) suitability for long-term use, (ix) low operating effort, and (x) minimal maintenance.

C. Results of the Design Process

1) Clarifying Objectives

Based on the identified system and user needs, design objectives were structured into an objectives table. The primary objective was to reduce ergonomic risk during lifting and transport, supported by secondary objectives related to safety, usability, durability, layout compatibility, and efficiency. This structure ensured traceability from stakeholder expectations to design targets, as shown in Table 2**.**

2) Establishing Functions

Function analysis was conducted using a black-box and transparent-box approach. The black-box (Fig. 5) model defines the transformation from operator input into the controlled transfer of box panels to the truck in a safe, healthy, and comfortable manner. The transparent-box (Fig. 6) decomposition further specifies sub-functions, including load support, pushing/pulling during transport, stabilization, safe placement at the destination, and operator–device interaction.

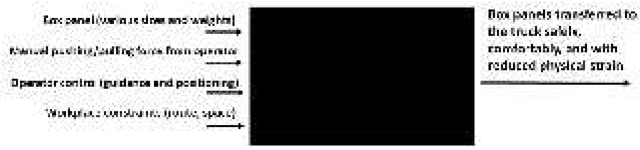

Figure 5. Black Box

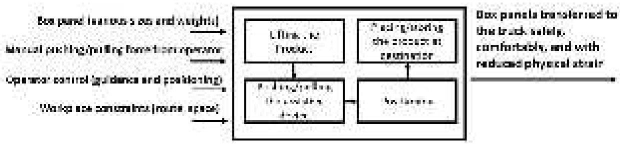

Figure 6. Transparent Box

Table 2. Translation of Objective by Representative User Needs into Engineering Design Specifications

Objective Representative by User Need	Engineering Specification	Objective Category	Supporting Reference
Easy to operate; not complicated; reduces physical effort during handling	Ergonomic interface, handle design, and user–device interaction	Comfort & usability	[11], [12], [13]
Avoid awkward postures (bending/reaching)	Working height alignment and transfer mechanism design		[11], [9], [10]
Prevent box panels from slipping/falling.	Stability system, load securing mechanism, and posture risk reduction	Safety & health	[19], [15]–[17]
Reduce injury risk (especially low back)	Reduction of manual lifting demand through mechanical assistance		[9], [10], [11]
Must carry heavy box panels safely	Structural strength and load-supporting system	Effectiveness	[8], [25]
Reduce transport time and improve flow.	Mobility system and controlled pushing/pulling mechanism		[25], [26]
Usable for other products/materials	Adaptable platform and modular support features	Versatility & durability	[25], [26]
Durable for long-term daily use	Material selection and robust structural design		[25], [26]
Preferably non-electric and low maintenance	Simple mechanical system with low energy requirement	Efficiency	[25], [18], [20]
Must work within existing layout; no fixed rails	Maintenance-friendly design and component simplicity		(measured on-site)

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3) Performance Specification

By integrating ergonomic assessment results, system constraints, and grouped user needs, a set of performance specifications was derived. Key requirements include sufficient load capacity (>37 kg), compatibility with box panel dimensions, stable transport without load shifting, ergonomic handle height for standing operation, and non-powered operation with minimal maintenance. These specifications are summarized in Table 3 and served as the basis for concept generation and evaluation.

Table 3. Performance Specification

No.	Aspect	Observed Condition	Performance Specification
1	Product load	> 37 kg	The box panel support system and frame shall be capable of supporting loads up to 37 kg.
2	Truck bed height	145 cm	The height of the product support/transfer point shall not be lower than 145 cm to enable direct placement on the truck.
3	Box panel length	80 cm	The length of the product support platform shall not be less than 80 cm.
4	Box panel width	60 cm	The width of the product support platform shall not be less than 60 cm.
5	Production floor condition	Limited space	The solution shall operate without installing fixed rails on the production floor.
6	Transport route constraint	-	The device shall be operable along the exit route with an approximate length of 15 m and a width of 2 m.

4) Determining Technical Characteristics

Quality Function Deployment (QFD) was applied to translate representative user needs into engineering design priorities. The analysis shows that safety- and load-related needs dominate the importance ranking, followed by usability and efficiency considerations.

The most critical technical characteristics identified from the QFD analysis include structural strength and load support, stability and load securing, mobility for pushing/pulling transport, ergonomic interface and working height alignment, and simplicity for low maintenance.

These characteristics represent the main design drivers and were used to guide the subsequent concept generation and concept selection stages.

5) Generating alternatives

Based on the prioritized technical characteristics identified through the QFD analysis, alternative design concepts were generated using a morphological approach. Three feasible concepts (Concept A, Concept B, and Concept C) were developed to represent different combinations of load support, mobility, stabilization, and transfer mechanisms. Concept A emphasizes higher mechanization, Concept B represents a fully manual but bulkier structure, and Concept C adopts a simple non-powered assistive solution. The complete morphological chart is omitted for brevity, and only the resulting concepts are carried forward for evaluation.

6) Evaluating alternatives

Concept evaluation was conducted using a weighted objectives method to compare the generated alternatives in a structured manner. Evaluation criteria were derived from representative user needs and QFD results, covering comfort and usability, safety and health, effectiveness, versatility and durability, and efficiency. Criterion weights were obtained from aggregated questionnaire responses of 35 users.

Three alternatives (Concept A, Concept B, and Concept C) were evaluated using the same criteria and weighting scheme. The evaluation results are summarized in Table 5, showing that Concept C achieved the highest total weighted score. Concept C provides a balanced solution that satisfies key ergonomic and operational requirements while maintaining simplicity and low maintenance, making it the most suitable option for further development.

Table 4. Pairwise Comparison (Zero–One Method) for Determining Criterion Weights

Criteria	C1	C2	C3	C4	C5	Total	Weights
C1 Comfort & usability	–	0	0	1	0	1	0,1
C2 Safety & health	1	–	1	1	1	4	0,4
C3 Effectiveness	1	0	–	1	1	3	0,3
C4 Versatility & durability	0	0	0	–	1	1	0,1
C5 Efficiency	1	0	0	0	–	1	0,1
Total	2	4	3	1	0	**10**	**1**

Criterion weights were determined using a zero–one pairwise comparison method. Each evaluation criterion was compared against the others based on relative importance as perceived by system users and supervisors. The resulting scores were normalized to obtain criterion weights, which

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were then used in the weighted objectives evaluation of design alternatives.

Table 5. Concept Evaluation Using the Weighted Objectives Method

No	Evaluation Criterion	Weight	Concept A	Concept B	Concept C
1	Comfort and usability	0,1	4	2	4
2	Safety and health	0,4	4	4	4
3	Effectiveness	0,	4	3	4
4	Versatility and durability	0,1	4	3	3
5	Efficiency (low effort & maintenance)	0,1	1	4	4
	Total	**1**	**3,7**	**3,4**	**3,9**

Table 5 presents the evaluation results of the three design alternatives using the weighted objectives method. Criterion weights were derived from aggregated questionnaire responses of 35 operators, reflecting the relative importance of each user-need category. Concept C achieved the highest total weighted score, indicating superior overall performance across ergonomic, safety, effectiveness, and efficiency criteria. Therefore, Concept C was selected for further development and final design.

7) *Improving details*

After Concept C was selected through the weighted objectives evaluation, the design was refined into a detailed configuration by specifying the main components, dimensions, and interface features. The final design focuses on providing stable load support, ergonomic operation, and smooth transport while remaining compatible with the existing layout constraints. The finalized configuration of the assistive device is illustrated in Fig. 5, showing the overall structure, lifting table, handle, and mobility system.

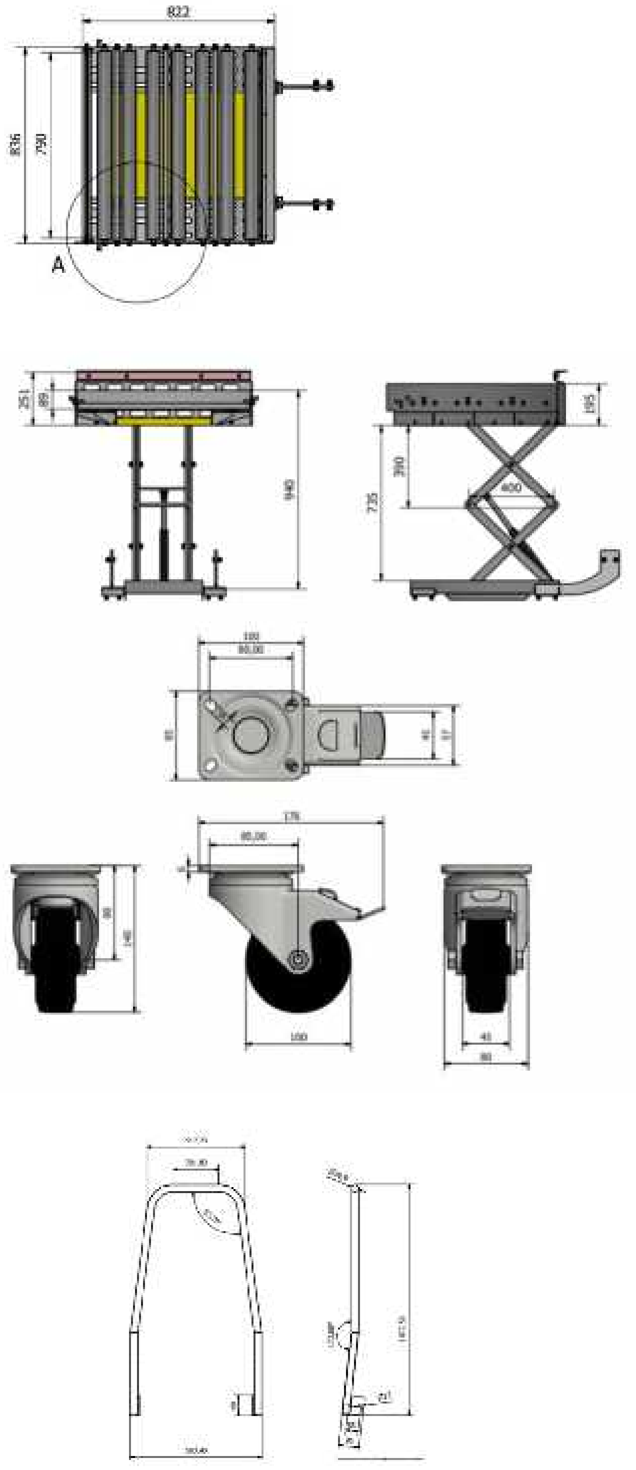

Figure 5. Final Configuration

Dimensioning was performed to ensure consistency with the identified system requirements and performance specifications. The main frame height was set to enable direct transfer to the truck bed, while the platform dimensions were defined to accommodate the maximum box panel size during transport. Handle height and grip dimensions were specified to support comfortable

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pushing and pulling during operation, and wheel diameter was selected to ensure stable movement along the transport route. The detailed dimensions of the main components are summarized in Table 6.

Table 6. Final Dimensions Used in the Assistive Device Design (cm)

Component	P	L	T	D	Remarks
Main frame (lifting cart frame)	95	75	145	–	Adjusted to the selected alternative
Box panel support table/platform	82	83	20	–	Adjusted to the selected alternative
Handle grip (handgrip)	51,77	–	102,75	2,68	Adjusted to the selected alternative
Wheel/caster	–	–	–	10	Adjusted to the selected alternative

The frame height was set to support transfer at the destination point, while the platform dimensions were defined to provide stable support for the box panels during transport. The handle grip dimensions were specified to improve operator comfort and control during pushing/pulling, and wheel diameter was selected to support stable movement along the transport route.

D. *Evaluation of Ergonomic Improvement*

Ergonomic improvement was evaluated by comparing baseline manual handling conditions with the proposed assistive device (Concept C) using three complementary indicators described in the methods: postural risk (REBA), biomechanical lifting demand (RNLE: RWL and LI), and psychophysical feasibility (Snook and Ciriello MAW). Baseline results indicate a high-risk posture (REBA = 12) and an overloaded lifting/carrying demand, where RNLE outputs show RWL values well below the actual handled loads, and Snook MAW estimates (≈12–13 kg) remain far lower than the box panel mass range (18–37 kg). The proposed device is expected to reduce manual lifting and awkward postures by supporting stable load transport and transfer, thereby lowering overall ergonomic risk (see Fig. 6 – Fig. 9). A consolidated before–and–after summary is provided in Table 7.

Table 7. Summary of Improvement Before and After Intervention

Ergonomic Indicator	Manual Handling	With an Assistive Device	Interpretation
REBA score	12	1	Reduced bending and improved posture during handling
Lifting Rasio (LI)	> 1.0	< 1.0	Lower low-back injury risk
Load-to-MAW ratio	> 1.0	< 1.0	Reduced overload condition
Overall ergonomic risk	High	Reduced	Engineering control improves safety and usability

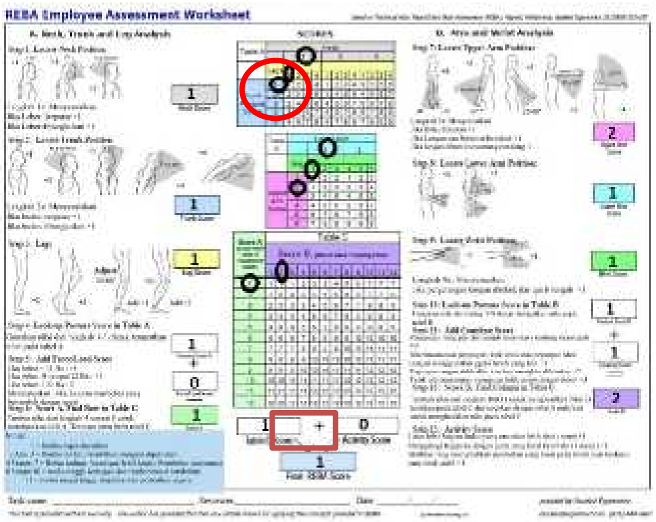

Figure 6: REBA assessment output after using the Assistive Device

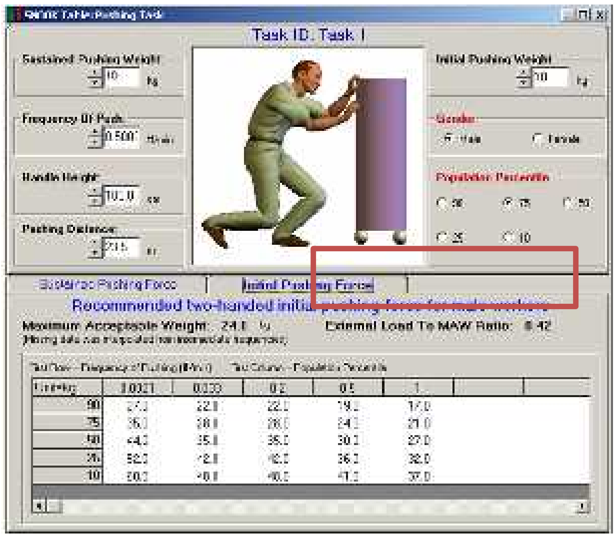

Figure 7: Snook output after using the Assistive Device

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Figure 8: RNLE output after using the Assistive Device

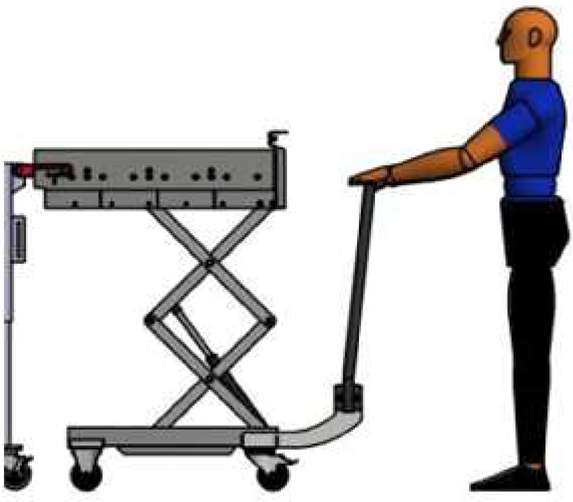

Figure 9: Illustration of an Assistive Device in use for Manual Material Handling

IV. CONCLUSION

The ergonomic evaluation demonstrates that the implementation of the assistive device significantly improves working conditions compared to manual handling. The REBA score decreased from 12 to 1, indicating a substantial reduction in postural risk and excessive bending during material handling activities. In addition, both the Lifting Index (LI) and Load-to-MAW ratio were reduced from values greater than 1.0 to below 1.0, confirming that the mechanical load on workers is maintained within acceptable ergonomic limits. Consequently, the overall ergonomic risk level was reduced from high to a controlled condition. These findings confirm that the proposed engineering intervention effectively enhances safety, usability, and workload management, thereby reducing the potential for musculoskeletal disorders and supporting a more sustainable and ergonomically sound work system.

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