

Advancing Economic Development in the APEC Region: Best Practices for Smart Human–Machine Collaboration in the Heavy Steel Construction Industry

Final Report

APEC Policy Partnership on Science, Technology and Innovation

October 2026



**Asia-Pacific
Economic Cooperation**



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Produced by

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1. Introduction to Smart Human–Machine Collaboration and Transformation Trends in the Heavy Steel Construction Industry

1.1 Overview of Regional Challenges and Workforce Dynamics in Heavy Steel Fabrication

The heavy steel fabrication sector across APEC economies is undergoing a period of significant transition driven by sustained infrastructure investment, modular construction demand, and the broader push toward industrial modernization. Across the region, steel fabrication continues to play a critical role in supporting large-scale public works, energy facilities, and transportation infrastructure, underscoring its strategic importance for economic development and supply chain resilience.

Despite these favorable demand conditions, the sector faces persistent structural challenges that constrain its capacity to scale and modernize. Fabrication enterprises must contend with fluctuations in raw material and energy costs, complex logistics associated with oversized and custom-engineered components, and increasingly stringent quality and occupational safety requirements. These pressures are compounded by pronounced workforce dynamics, including the aging of experienced welders and technicians and a growing shortage of skilled labor. As senior workers approach retirement, difficulties in skill transfer and workforce renewal are creating tangible risks to productivity, delivery schedules, and long-term competitiveness across many APEC economies.

In response, manufacturers are accelerating the adoption of automation, digitalization, and smart manufacturing solutions, including advanced welding automation, AI-assisted inspection, and collaborative robotic systems. While these technologies offer opportunities to improve precision, consistency, and workplace safety, adoption remains uneven. Small and medium-sized enterprises, in particular, often face barriers related to capital availability, technical integration capacity, and access to structured upskilling pathways.

Within this context, human–machine collaboration is emerging as a key strategic approach for addressing both technological and workforce constraints. By enabling closer, safer, and more flexible interaction between skilled workers and intelligent systems, human–machine collaboration can enhance productivity, stabilize quality, and reduce physical workload in demanding fabrication environments. At the same time, it supports broader workforce participation by lowering physical barriers to entry and enabling new technology-oriented roles. These dynamics align closely with APEC’s priorities on human capital development, inclusive growth, and resilience, highlighting the importance of coordinated regional efforts to share best practices and strengthen implementation capacity across economies.

1.2 Smart Manufacturing and Human–Machine Collaboration Technologies: Applications and APEC Capacity-Building Efforts

In response to demographic shifts, workforce transitions, and growing demand for automation in the heavy steel construction industry, APEC has supported Chinese Taipei in leading the project. Advancing Economic Development in the APEC Region: Best Practices for Smart Human-Machine Collaboration in the Heavy Steel Construction Industry (PPSTI 203 2024A). Backed by the ASF Supply Chain Connectivity (SCC) Sub Fund, the project is strategically positioned to strengthen supply chain resilience by enabling upstream suppliers and fabrication enterprises to adopt emerging digital and robotic technologies. Through its design, the project advances APEC’s collective objectives in modernizing production systems, improving industrial productivity, and ensuring inclusive access to technological upgrading across diverse economies.

A central focus of the project is the demonstration and dissemination of human–machine collaboration (HMC) applications, including digital welding innovations, robotics-enabled workflow optimization, and AI-supported sensing, inspection, and process control. These technologies offer significant advantages for heavy steel construction, where precision welding, repetitive handling, and hazardous working environments remain major operational constraints. By integrating collaborative robots, autonomous positioning systems, and intelligent welding automation, economies can reduce defect rates, improve real-time monitoring, and enhance safety performance across fabrication lines. Moreover, HMC technologies can lower the physical demands associated with welding work, thereby opening opportunities for a broader and more diverse workforce—including women and new entrants—to participate in advanced manufacturing sectors. This aligns with APEC’s priority on women’s economic empowerment and inclusive workforce development.

To operationalize these goals, a two-day APEC workshop was held on 18–19 March 2026 in Kaohsiung, Chinese Taipei, and organized by the Metal Industries Research & Development Centre (MIRDC). The event gathered representatives from government agencies, industry, academia, and research institutions across APEC economies. Through keynote presentations, expert panels, and technology demonstrations, participants examined emerging HMC and welding technologies and explored practical pathways for accelerating smart manufacturing adoption. Workshop sessions featured discussions on AI-enabled welding innovations, VR-assisted remote operation, safety and risk management for collaborative robots, and cross-economy case studies highlighting real-world applications in fabrication, logistics, and robotic handling operations. Further, dedicated discussions addressed safe human–robot interaction in heavy steel fabrication settings, including

considerations for tasks commonly performed by women and new operators. These exchanges provided participants with actionable insights into how HMC can improve productivity, reduce occupational hazards, and enhance resilience in steel construction supply chains.

By anchoring its activities in both technology demonstration and capacity building, the project contributes directly to APEC's broader objectives in digital transformation, innovation-driven growth, and human capital development. The workshop enabled economies at different stages of industrial digitalization to exchange lessons learned, identify common challenges, and explore opportunities for future collaboration, including pilot demonstrations, joint R&D activities, and workforce training initiatives. Ultimately, the project advances the foundation for a more resilient, sustainable, and technology-enabled heavy steel construction ecosystem across the APEC region, ensuring that smart manufacturing benefits are shared inclusively and equitably.

2. Research and Implementation of Smart Human–Machine Collaboration Technologies Across APEC Economies

Based on the experiences of multiple APEC economies presented in this section, several common trends can be identified regarding the research and implementation of smart human–machine collaboration (HMC) technologies. First, many economies are facing structural challenges such as labor shortages, aging workforces, and increased safety risks in high-intensity industrial operations. These challenges have driven growing interest in human-centered automation and collaborative robotic solutions, positioning HMC not only as a means to improve productivity, but also as a key approach to enhancing workplace safety, supporting workforce transitions, and improving job quality.

Second, the cases demonstrate that HMC technologies are particularly effective in demanding manufacturing tasks such as welding, handling, and pick-and-place operations, where repetitive or hazardous conditions are present. By enabling intelligent machines to perform high-risk or physically demanding tasks while maintaining human oversight and decision-making, HMC supports a complementary human–machine interaction model. This approach is especially relevant for economies with a high proportion of small and medium-sized enterprises (SMEs), as it allows for gradual adoption of advanced technologies under constrained resource conditions.

Finally, the experiences across economies indicate that successful deployment of HMC depends not only on technological capability, but also on workforce training, organizational readiness, and cross-sector collaboration. Insufficient skills development or institutional

support can limit the broader diffusion of these solutions. Overall, the cases provide transferable lessons for APEC economies and highlight the adaptability and scalability of smart human–machine collaboration across different industrial contexts and stages of development.

2.1 Canada

How R&D innovation is levelling the field and opening doors for new Canadian talent and gender equality (Canada, Soroush Karimzadeh, Chief Executive Officer of Novarc Technologies)

Soroush Karimzadeh highlighted that welding remains one of the most physically demanding and least inclusive industrial trades, facing persistent labor shortages and extremely low participation from women and younger workers across APEC economies. Traditional manual welding and early generations of automation have struggled to adapt to highly variable welding conditions, limiting productivity gains and reinforcing high physical and skill barriers to entry.

In response, Mr. Karimzadeh emphasized how R&D-driven innovation in autonomous welding is fundamentally reshaping both the industry and its workforce. Novarc’s integration of robotics, AI, and real-time vision enables welding systems to perceive, adapt, and respond dynamically during operation, significantly reducing physical strain, improving safety, and delivering consistent quality. By shifting welding from a manual, hazardous task to a technology-enabled process, automation lowers entry barriers and enables individuals from more diverse backgrounds to participate as operators, supervisors, and robotics specialists.

Canadian case experiences demonstrated that autonomous welding not only improves productivity and return on investment, but also creates safer, cleaner, and more accessible work environments that support gender inclusion and talent development. Mr. Karimzadeh concluded that inclusive automation represents both an industrial and a societal transformation. Continued investment in R&D, skills development, and cross-economy knowledge sharing on a voluntary and mutually agreed basis within APEC will be essential to scale these innovations and foster equitable, sustainable growth in advanced manufacturing.

Novarc - Where the Future of Welding is Already at Work

Our diverse global team—including 20% women—builds technologies that lower barriers to enter welding and robotics.

Global Leader in Welding Automation

- Pioneering applied robotics and AI to revolutionize industrial welding
- Trusted worldwide across multiple industries

137 Employees Across 6 Countries

- Australia | Canada | Ireland | Saudi Arabia | United Kingdom | United States
- HQ: Burnaby, BC | Customer Experience Center: Houston, TX
- 27 (~20%) Women including 2 in SLT (~20%)

Strong IP Portfolio

- 21 Granted Patents, 24 Patent Applications, Robust Trade Secret Program, 18 Registered Trademarks



One of the only welding automation companies with women in the Senior Leadership Team.

Figure 1. Inclusive robotics innovation expanding women’s participation in welding and automation.

2.2 Japan

Trends in Robotics Technology and Japan Yamazen’s Activities (Japan, Mizobe Kazuhide, TFS of Yamazen group)

Mr. Mizobe Kazuhide highlighted that Japan’s manufacturing sector is facing severe labor shortages driven by a rapidly aging population, making automation and productivity improvement urgent domestic priorities. Traditional manufacturing processes are increasingly constrained by workforce limitations, variability in production, and rising demands for flexibility and quality. Against this backdrop, robotics is evolving from task-specific automation toward more adaptive, intelligent, and human-collaborative systems.

In response, Yamazen has focused on promoting collaborative robots, autonomous mobile robots, and AI-enabled automation as practical solutions for factory and logistics environments. Mr. Mizobe emphasized the integration of AI vision, torque and sensor feedback, and simulation technologies to enable flexible robot deployment, safe human–robot collaboration, and improved accuracy in inspection, picking, and assembly tasks. Yamazen’s Total Factory Solution approach combines hardware, software, and system integration to deliver one-stop solutions tailored to diverse manufacturing needs.

He further highlighted emerging trends toward Physical AI and humanoid robots, supported by large-scale data collection and virtual simulation platforms. Yamazen’s initiatives, including the development of physical data generation centers, aim to accelerate learning, standardize robotic skills, and enable scalable automation across different robot

types. In conclusion, Yamazen's experience underscores the importance of integrating AI, robotics, and human-centric design to support sustainable manufacturing transformation across APEC economies.

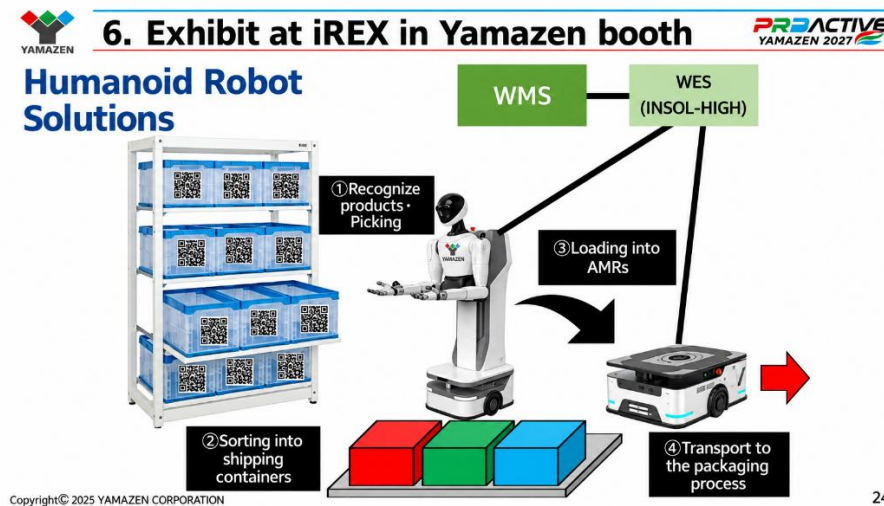


Figure 2. Yamazen humanoid robot automating picking, sorting, and AMR-based logistics through system integration.

2.3 Malaysia

Collaborative RFID Inventory Robot: Enhancing Interaction Between Machines, Librarians and Heavy Steel Industry (Malaysia, Professor Yap, Kian Meng, SUNWAY UNIVERSITY)

Professor Yap Kian Meng presented a human-centric approach to human-robot collaboration through the development of a collaborative RFID inventory robot designed to address long-standing challenges shared by library and heavy steel industry environments. He highlighted that large-scale inventory environments suffer from labor-intensive manual scanning, high error rates due to misplacement, and signal interference from dense or metallic surroundings, making traditional RFID and manual inspection methods inefficient and difficult to scale.

To respond to these challenges, Professor Yap introduced an autonomous RFID robotic system that integrates intelligent navigation, multi-RFID scanning, and AI-based interference recovery algorithms. In library environments, the robot emulates librarians' shelf-reading tasks, autonomously navigating narrow aisles, detecting misplaced or missing books, and synchronizing real-time inventory data to digital systems. Advanced scanning strategies and learning-based prediction models significantly reduce redundant scanning while maintaining

accuracy comparable to handheld devices, enabling librarians to transition from repetitive manual work to supervisory and user-focused roles.

Importantly, Professor Yap demonstrated that the same AI-RFID robotic framework can be extended to heavy steel industries, where metal interference traditionally limits RFID performance. By optimizing antenna geometry, scanning paths, and AI-driven signal recovery, the system achieves high-accuracy, real-time tracking of steel components, tools, and materials, supporting ERP and logistics integration.

The presentation illustrated how collaborative AI-robot systems can connect machines and human operators across seemingly disparate domains. By enhancing efficiency, scalability, and safety, this approach offers a transferable model for inventory modernization and human-robot collaboration across APEC economies.

Solution 2: Multi-RFID Scanner



Figure 7: Efficient Robot Scanning Path

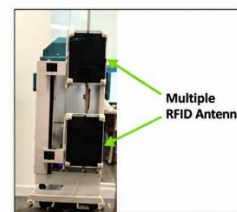


Figure 8: Multiple RFID Scanner

- **Use of Multiple RFID Scanner:** a We deploy multiple use of RFID scanner that is able to detect multiple rows in single travel path.
- **Two Scan per Row:** Utilizes intelligent system, the robot is able to rearrange and store the scanned books.
- **Increase Efficiency:** This reduce number of times the robot have to pass to scan and collect all of the books in different row location.

Figure 3. Multi-RFID scanning captures multiple rows in a single pass

2.4 Mexico

Robotics Technology in Mexico (Mexico, Antonio Balbín, Chief Innovation Officer of INNOVATIVE AUTOMATION SOLUTIONS)

Antonio Balbín highlighted that Mexico's robotics and automation landscape is advancing rapidly in response to labor shortages, increasing production complexity, and the integration of Mexico into global manufacturing supply chains. As a major hub for automotive, electronics, and metal processing industries, Mexico faces strong pressure to improve productivity, quality consistency, and workplace safety while remaining

cost-competitive. Traditional automation, while widely adopted, is increasingly constrained by flexibility and workforce skill gaps.

In response, Mr. Balbín emphasized Mexico's shift toward intelligent automation and human–robot collaboration. Innovative Automation Solutions has focused on deploying collaborative robots, AI-enabled vision systems, and flexible automation cells that can be quickly adapted to changing production demands. These technologies lower barriers to adoption for small and medium-sized enterprises, support rapid reconfiguration, and allow human workers to move into higher-value supervisory and process-optimization roles. Emphasis was placed on practical system integration, operator-friendly interfaces, and workforce upskilling to ensure successful deployment.

Mr. Balbín also underscored the importance of cross-border collaboration and knowledge transfer within APEC, particularly in aligning standards, sharing best practices, and developing talent for advanced manufacturing. In conclusion, Mexico's experience demonstrates how pragmatic, human-centric robotics and AI adoption can strengthen industrial resilience and competitiveness, offering valuable lessons for other APEC economies pursuing inclusive and scalable automation strategies.

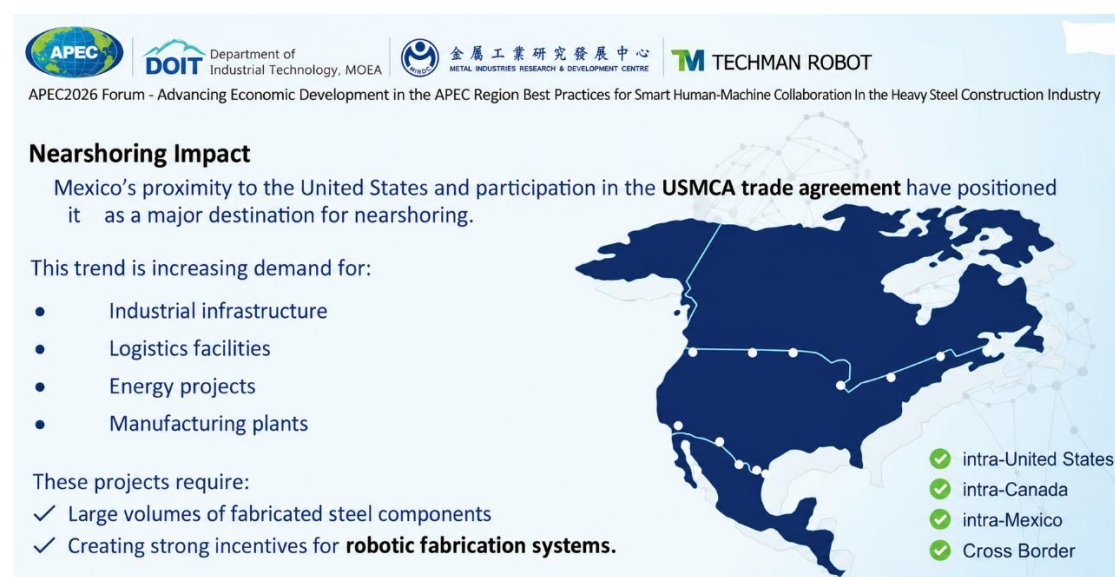


Figure 4. USMCA-driven nearshoring positions Mexico as a key manufacturing base, increasing steel construction demand and accelerating robotic fabrication.

2.5 Singapore

*Recent Development in Human–Robot Collaboration: Singapore's Perspective (Singapore, Dr. Yau Wei Yun, Division Head (Robotics & Autonomous Systems) of A*star I2R)*

Dr. Yau Wei Yun presented Singapore's approach to advancing human–robot collaboration in response to structural challenges including rapid population aging, persistent labor tightness, and large-scale domestic infrastructure demands. With a shrinking local workforce and increasing reliance on foreign labor, Singapore faces strong pressure to deploy intelligent robots that can operate safely and effectively in real-world, human-centric environments such as ports, airports, construction sites, healthcare facilities, and public spaces.

To address these needs, Dr. Yau emphasized a progressive framework of human–robot interaction, collaboration, and teaming, supported by higher levels of robotic intelligence. A*STAR I2R's response focuses on embodied AI, multi-modal perception, autonomous navigation, dexterous manipulation, and intrinsic safety. Key technological enablers include map-lite and GNSS-free navigation, semantic understanding of environments, tactile-guided manipulation, and safety-aware control architectures designed to mitigate risks when robots operate in close proximity to people, including risks associated with AI hallucination.

Dr. Yau highlighted multiple deployment cases, such as autonomous patrolling for public security, construction inspection robots aligned with digital building models, automated aircraft inspection systems, and healthcare assessment robots collaborating with medical staff. These applications demonstrate how robots can augment human capabilities, reduce physical risk, and improve productivity without displacing human oversight.

To summarize, Singapore's experience underscores that safe, intelligent, and human-centric human–robot collaboration is essential for sustainable growth. Continued policy support, real-world validation, and voluntary cross-economy knowledge sharing within APEC will be critical to scaling these solutions responsibly.

Developed Robotic Intelligence for Deployment in Physical World

KEY AUTONOMOUS NAVIGATION CAPABILITIES

Harnessing AI and Multi-modal Perception to enable robust Navigation in cluttered, unstructured and dynamic environments with different locomotion modes.



KEY DEXTEROUS MANIPULATION & HRI CAPABILITIES

Harnessing the power of generative AI and rich data, robots can perceive through multiple sensory inputs to provide effective and dexterous interaction between robots and other nearby agents to complete tasks efficiently.



Figure 5. Robotic intelligence enabling safe and efficient human–robot collaboration in

2.6 Chinese Taipei

(1) AI-Driven Service Robotics Ecosystem and S&T Policy in Chinese Taipei (Chinese Taipei, Dr. Ren C. Luo, Irving T. Ho Chair Professor, NTU¹)

Across APEC economies, population aging, declining birth rates, and persistent labor shortages are placing growing strain on healthcare, manufacturing, logistics, and public services. As work environments become more complex, traditional automation systems struggle to adapt to real-time variability and human-centric operational needs. At the same time, much of today's artificial intelligence remains focused on digital data processing, lacking the capability to interact effectively and safely within physical environments alongside human workers. This gap limits both scalability and real-world impact.

To address these shared challenges, APEC members are advancing smart human-machine collaboration technologies that emphasize system integration and application-driven design. These technologies integrate generative AI, embodied intelligence, real-time sensing, and edge computing to enable adaptive and safe collaboration between humans and machines. Through dual-core architectures that separate high-level AI reasoning from time-critical motion control, and through the use of digital twin platforms for virtual training and validation, deployment risks are reduced while reliability and trust are enhanced.

Implementation experiences across APEC economies demonstrate tangible benefits. In healthcare, collaborative service robots integrated with hospital information systems support logistics and routine tasks, easing workforce pressure and allowing professionals to focus on care requiring expertise and human judgment. In logistics and warehousing, autonomous mobile systems work in coordination with human operators via AI-enabled scheduling, improving efficiency, safety, and supply chain resilience.

In summary, smart human-machine collaboration technologies offer an effective pathway for addressing structural demographic and economic challenges across APEC economies. By supporting real-world validation, mutual knowledge sharing, and policy coordination, APEC can accelerate responsible and scalable adoption, contributing to inclusive productivity growth and long-term regional resilience.

¹ National Taiwan University

Conclusions and Recommendations (1/2)



A New Imperative: Driven by aging populations and labor shortages, AI service robots have evolved from a niche tech sector into a critical capability for social resilience and sustainable development.



APEC as a Testing Ground: Service robots provide an ideal STI (Science, Technology, and Innovation) policy practice arena to examine how governance and pilot applications can accelerate scalable, trustworthy tech deployments.



Chinese Taipei's Role: Building on a robust ICT and automation foundation, Chinese Taipei is accumulating practical experience in cross-system integration, serving as a vital empirical testing ground for APEC members.

Conclusions and Recommendations (2/2)



1. Leverage PPSTI as a Coordination Platform

Treat service robots as a flagship STI issue to foster continuous policy and tech dialogue among APEC members.



2. Support Demand-Driven Pilot Applications

Encourage member economies to champion real-world pilots in healthcare and logistics to build empirical data on feasibility and business models.



3. Deepen APEC Connectivity

Build systematic knowledge-sharing mechanisms for case studies and best practices, promoting trustworthy cross-economy collaboration.



4. Chinese Taipei as a Knowledge-Sharing Partner

We remain committed to accumulating real-world validation data and collaborating with APEC members to explore policy and practical applications across diverse societal contexts.

Figure 6. Key conclusions and recommendations for promoting smart human–machine collaboration across APEC economies.

(2) *Examine the future technological challenges and opportunities for human-machine collaborative robots in heavy steel construction field Chinese Taipei,*

Dr. Chiu, Cheng-Chang, Director of Metal Industries Research & Development Centre

Dr. Chiu, Cheng-Chang, Director of Metal Industries Research & Development Centre, emphasized that manufacturing sectors across APEC economies are facing converging challenges, including skilled labor shortages, difficulties in knowledge transfer, and growing demand for low-volume, high-mix, and high-value production. Traditional machine-centered automation and Industry 4.0 frameworks are increasingly insufficient for managing complex processes, irregular materials, and customized manufacturing, while maintaining consistent quality and real-time responsiveness.

In response, Dr. Chiu highlighted a strategic transition toward human-centric Industry 5.0, where smart human–machine collaboration enhances human expertise rather than

replacing it. Key approaches include integrating artificial intelligence, collaborative robotics, advanced sensing, and process-aware digital twin architectures. Digital twins enable virtual simulation, validation, and optimization of processes before deployment, while real-time data synchronization between digital and physical systems supports adaptive control, predictive decision-making, and risk reduction. AI-driven vision and closed-loop feedback systems further improve quality assurance, defect detection, and operational reliability.

Dr. Chiu presented several implementation cases, including collaborative welding in semiconductor and heavy industries, deformable material handling, and precision inspection in metal forming. In these applications, intuitive human–robot collaboration interfaces accelerate skill transfer, improve safety, and address workforce constraints, while digital twin technologies reduce uncertainty and support scalable deployment.

Dr. Chiu underscored that smart human–machine collaboration is a critical enabler of resilient, high-value industrial transformation across APEC economies. By aligning advanced technologies with human expertise, strengthening real-world validation, and promoting cross-economy knowledge sharing APEC members can support sustainable growth and long-term industrial competitiveness.

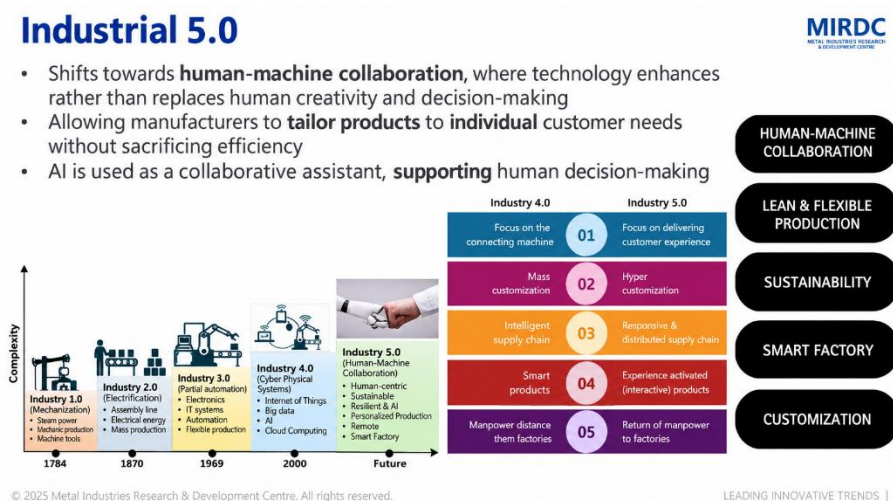


Figure 7. Industry5.0 focuses on human–machine collaboration to enable flexible, customized, and sustainable smart manufacturing

(3) *Advancing Industry Transformation through AI Human–Robot Collaboration.* (Chinese Taipei, Dr. Huang Scott, Chief Operating Officer of Techman robot)

Dr. Huang Scott, Chief Operating Officer of Techman Robot, emphasized that industries across APEC economies are facing increasing pressure from skilled labor shortages, safety requirements, and the need for flexible, high-quality production. Conventional automation alone is no longer sufficient to address dynamic shop-floor conditions or complex tasks such as welding, inspection, and mobile manipulation, highlighting the importance of closer and safer collaboration between humans and intelligent robots.

Dr. Huang presented an AI-driven human–robot collaboration framework built around the “See–Think–Act” paradigm. By integrating AI vision, perception intelligence, and autonomous decision-making directly into collaborative robots and mobile manipulators, robots can better understand their environment, support human workers, and adapt to task variations with minimal reprogramming. The use of digital twins and large-scale synthetic and real-world data generation further accelerates the training, validation, and deployment of physical AI, enabling consistent performance across different applications and robot fleets.

Practical case studies, particularly in welding and smart manufacturing, demonstrated that AI-enabled cobots can significantly lower the entry barrier for operators, ensure consistent quality, improve productivity, and enhance workplace safety. Dr. Huang underscored that AI-powered human–robot collaboration is a critical pathway for sustainable industrial transformation, and that continued talent development, ecosystem partnerships, and voluntary cross-economy knowledge sharing within APEC are essential to scale these solutions responsibly.

Academy Global Footprint: Indiana, USA Case **TELABOTICS**

Smart Manufacturing
Focused on the manufacturing heartland of the U.S. Midwest, establishing an AI-powered collaborative application demonstration center

Localized Production
Collaborate with local system integrators to deliver AI solution packages that meet North American industrial standards

Strategic Partner
Strengthen engagement with the supply chain in Indiana to accelerate automation upgrades in the automotive and heavy industries

Partners:
Telabotics
ADVANCED R&D & INNOVATION
Purdue Polytechnic Institute
Purdue School of IE
WORKFORCE DEVELOPMENT ECOSYSTEM
Purdue MEP
Vincennes University
Gene Haas Center
WJ Jasper Campus
Marian University

Purdue School of IE
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A top-ranked research institution advancing human-robot collaboration systems and smart factory algorithms.
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Purdue Polytechnic Institute
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Focusing on applied engineering, robotics integration, and hands-on workforce curriculum development.

Solving the Shortage of manufacturing technicians
CONFIDENTIAL
See · Think · Act

Figure 8. Indiana case showcasing AI-enabled smart manufacturing and localized partnerships to develop skilled manufacturing talent

*(4) Virtual Force Sensing for Safe Human–Robot Collaboration in Smart Manufacturing
(Chinese Taipei, Professor Chai-Chieh Lan of NTU)*

Presented by Professor Chai-Chieh Lan of Chinese Taipei (NTU), this session addressed the critical role of virtual force and torque sensing in enabling safe human–robot collaboration in smart manufacturing. The presentation highlighted that, while harmonic drive actuators are widely adopted for their high torque density, compactness, and zero backlash, their strong nonlinear and history-dependent hysteresis poses significant challenges for accurate force/torque estimation. Conventional solutions relying on physical torque sensors increase cost, weight, and mechanical complexity, limiting their practicality for large-scale deployment in collaborative and humanoid robots.

To overcome these constraints, Professor Lan introduced a mechanical–learning co-design approach for virtual torque sensing. By incorporating a deliberately compliant element within the actuator and leveraging LSTM-based deep learning models, the proposed method enhances the observability of hysteresis behavior and enables accurate torque estimation without adding physical sensors. Experimental validation, including an industrial helmet grinding application, demonstrated that the virtual sensing approach can achieve accuracy comparable to skilled human workers and close to that of physical torque sensors, while maintaining low latency suitable for safety-critical interactions.

The presented technology offers a compact, cost-effective, and scalable solution for force-aware robotic systems. It provides a practical pathway for APEC economies to advance safe, efficient, and economically sustainable human–robot collaboration in smart manufacturing and related industries.

Conclusions

- Mechanical compliance enhances learning observability
- LSTM accurately captures hysteresis behavior
- Compact, sensorless torque estimation is achievable
- Suitable for humanoid and collaborative robots as **virtual torque sensors**

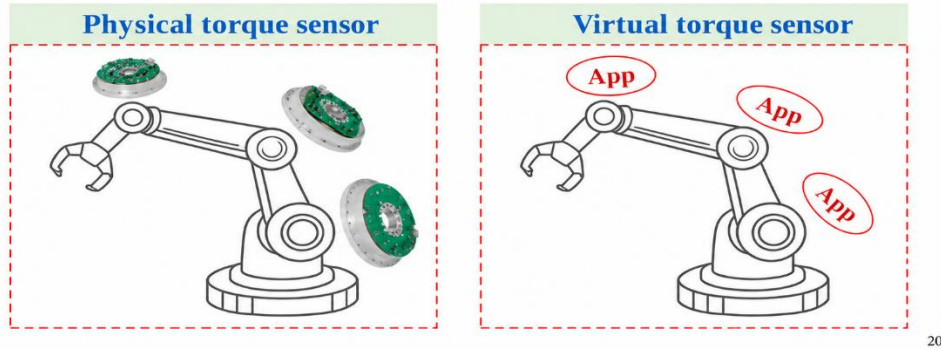


Figure 9. Comparison Between Physical and Virtual Torque Sensing

(5) Shaping the Next Industrial Era: AI-Enabled Robotics from ITRI's Strategic View (Chinese Taipei, General Director Officer Huang shu of ITRI)

Presented by General Director Officer Huang shu of Chinese Taipei (Industrial Technology Research Institute, ITRI), this session outlined ITRI's strategic vision and technological roadmap for advancing AI-driven robotics in response to labor shortages, aging societies, and the growing demand for smart manufacturing across the APEC region. The speaker emphasized that the convergence of AI, robotics, and high-fidelity simulation is transforming traditional industrial robots into intelligent, autonomous systems capable of flexible and human-centric operations. ITRI's approach is built on a two-track strategy: adding AI value and software intelligence to existing robotic platforms while simultaneously developing key components and next-generation robots such as modular manipulators, AMRs, quadrupeds, and humanoid systems.

The presentation highlighted ITRI's strengths in modular joint design, robot cell controllers, and digital twin-based simulation platforms that enable rapid deployment, easy customization, and cost-effective maintenance. A particular focus was placed on sim-to-real technologies, which bridge the gap between virtual training and real-world execution, improving safety, reliability, and development efficiency. Demonstrations across manufacturing, inspection, logistics, and service applications illustrated the scalability of these solutions. To conclude, the speaker underscored the organization's role in the global

robotics ecosystem, leveraging advanced semiconductor supply chains, ICT capabilities, and precision manufacturing expertise, and called for stronger APEC collaboration to jointly build a sustainable, intelligent, and competitive AI robotics industry for the next industrial era.

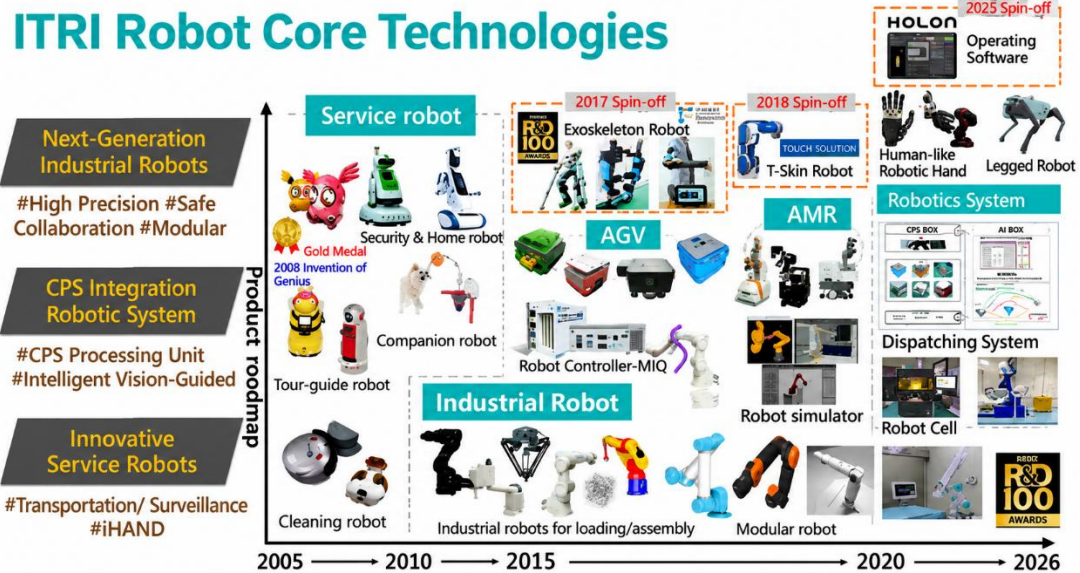


Figure 10. ITRI Robot Core Technologies.

2.7 USA

Rethinking the Skills Gap: Lessons from AI Vision Inspection and Collaborative Robots (USA, Chen Caleb, Manager of Telabotics)

Mr. Chen Caleb of the United States, Manager at Telabotics, this session examined the manufacturing skills gap from a practical, adoption-focused perspective, drawing on real-world experience with AI vision inspection systems and collaborative robots. The speaker emphasized that while labor shortages and upskilling needs are widely recognized across APEC economies, a less visible but equally critical challenge lies in usability. Many advanced manufacturing systems remain underutilized not because workers lack capability, but because technologies are designed primarily for engineers rather than frontline operators.

Through case studies from small and medium-sized manufacturers, the presentation demonstrated that usability directly determines participation, consistency, and ultimately productivity. When AI and robotics tools are intuitive enough for operators to configure, adjust, and improve independently, adoption accelerates and systems continue to deliver value over time. Examples showed that collaborative robots and AI inspection platforms, when designed with user-centered interfaces and feedback loops, can reduce onboarding time,

empower operators to take ownership, and create new hybrid roles rather than replace human skills.

The presentation argued that addressing the skills gap requires rethinking both technology design and workforce strategy. Rather than focusing solely on training more specialists, APEC economies should promote usability as a core requirement in smart manufacturing deployment. By designing systems that ordinary users can operate with confidence, industries can broaden participation, strengthen resilience, and achieve sustainable productivity gains aligned with inclusive economic growth.

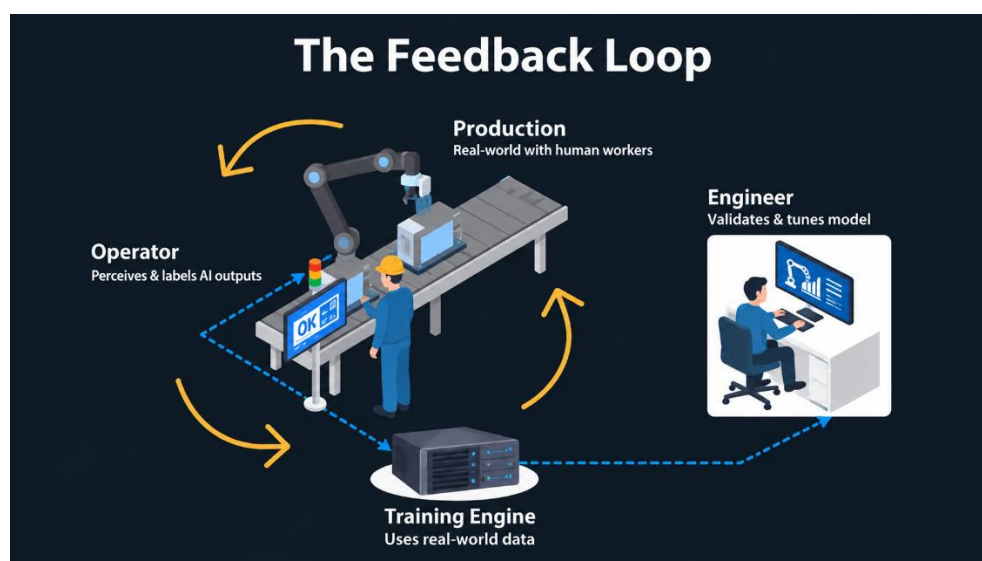


Figure 11. The Feedback Loop for Usable AI in Manufacturing

2.8 Viet Nam

(1) Foundation Models for Robot Learning and Interaction, (Viet Nam, Prof Tan Yap Peng of Vin University)

Professor Tan Yap Peng of Vin University emphasized that APEC economies are facing a critical convergence of necessity and capability in robotics, driven by shrinking workforces, aging societies, and increasing demand for services and hazardous tasks that human labor is less able or willing to perform. Conventional task-specific robots require extensive engineering effort and lack generalization, making them costly, inflexible, and difficult to scale across diverse environments and applications.

To address these limitations, Professor Tan highlighted a paradigm shift toward foundation models for robotics, enabling the transition from specialized systems to general-purpose physical AI. By integrating vision, language, and action into unified models, robots can acquire emergent reasoning and generalization capabilities from large-scale data rather than explicit task-by-task programming. Vision-Language-Action models allow robots to interpret instructions, understand unstructured environments, and directly translate intent into action. Supporting strategies include the use of internet-scale data, simulation, and real-world demonstrations, complemented by memory-augmented architectures to improve long-horizon task performance and reduce cumulative errors.

Demonstrations show that a single foundation model can support multiple tasks such as object assembly, laundry folding, and service operations, illustrating the potential for scalability and cross-domain transfer. Professor Tan also underscored key challenges, including sim-to-real gaps, safety risks, and action hallucination, which require robust validation and safety-aware design.

In conclusion, foundation models represent a transformative pathway for scalable, adaptable, and human-centric robotics across APEC economies, warranting continued research collaboration and mutual data sharing.

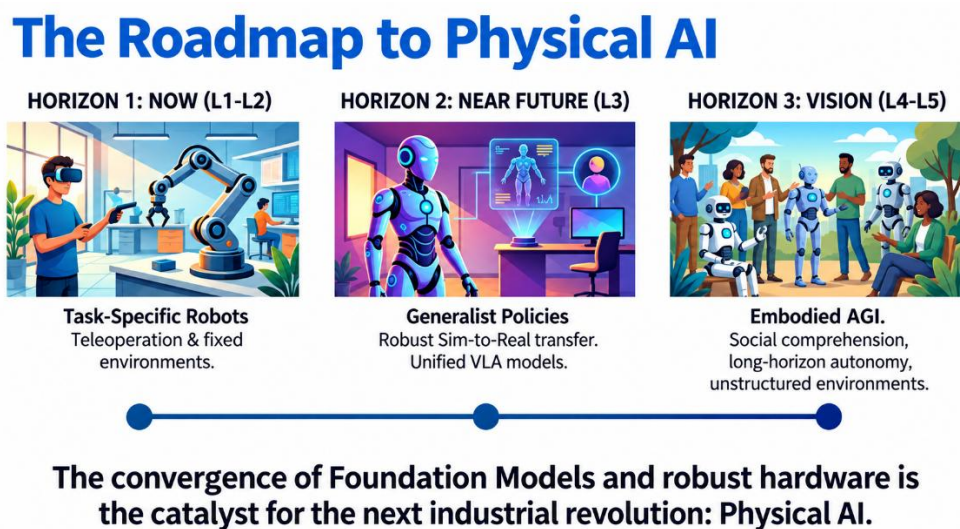


Figure 12. Roadmap to Physical AI showing the progression from task-specific robotics to generalist foundation models and embodied AI

(2) Manufacturing Efficiency and Precision: Trends and Practical Implementation in Viet Nam (Viet Nam, Bui Van Chi Director of Temas Engineering JSC)

Presented by Mr. Bui Van Chi, Director of Temas Engineering JSC of Viet Nam, this session provided an industry-driven overview of how manufacturing efficiency and precision are evolving in Viet Nam amid global supply chain restructuring, rising labor and energy costs, and increasing demands for traceability and sustainability. Drawing on extensive experience in automation system integration, the speaker highlighted that while advanced machines, sensors, and AI technologies are increasingly accessible, the fundamental challenge for many Viet Nam factories lies in system architecture and integration maturity rather than hardware availability. The presentation emphasized a structured transformation pathway, beginning with process stabilization to reduce uncontrolled variability, followed by consistent measurement and transparency, and only then advancing toward optimization and intelligent control.

Practical implementation cases from precision machining lines illustrated how integrating robotics, digital measurement, product-level traceability, and centralized data platforms can shift manufacturing operations from labor-dependent processes to architecture-driven, data-enabled control. These transformations resulted in improved repeatability, reduced downtime, enhanced traceability, and the transition from reactive to preventive management.

Mr. Bui underscored that sustainable manufacturing competitiveness in Viet Nam will depend on disciplined engineering practices, controlled variability, and a strategic approach to digitalization. Long-term success requires investment in engineering talent, local system integration capabilities, and coherent digital roadmaps, supported by collaboration among industry, academia, and government. Viet Nam is positioned to move from cost-driven manufacturing toward precision-driven competitiveness as the next phase of its industrial development.



KEY TAKEAWAYS



Figure13: Key Takeaways for Manufacturing Transformation

3. Smart Human–Machine Collaboration Solutions in Practice: Selected Case Studies

These case studies were selected based on relevance to high-risk tasks, scalability for SMEs, and applicability across multiple APEC economies.

This section presents a set of representative case studies that illustrate how smart human–machine collaboration (HMC) is being implemented in real industrial environments to address operational variability, safety concerns, and workforce constraints. The selected examples focus on practical, field-ready solutions applied to demanding manufacturing tasks such as welding, handling, and pick-and-place operations, where close interaction between human expertise and intelligent machines is required. Together, these case studies demonstrate how HMC can enhance process stability, improve safety and quality, and maintain flexibility in complex production settings, while remaining accessible and scalable across different industrial contexts.

3.1 Welding weave path laser tracking

The welding weave path laser tracking case study aligns closely with implementation experiences shared by Canada; Japan; Mexico; Chinese Taipei; , and, where precision welding under high variability and elevated safety risk remains a persistent industrial challenge. These economies commonly emphasized the need to stabilize welding quality in complex geometries and multi-pass operations while reducing reliance on highly experienced manual welders. The laser-tracked weave welding solution directly addresses these needs by maintaining accurate welding trajectories despite joint deformation, inconsistent fit-up, and dynamic speed changes.

In advanced manufacturing environments, the integration of laser sensing with real-time path correction supports consistent weld bead formation and penetration control, even under irregular conditions. This capability mirrors efforts in Canada and Japan to deploy adaptive welding systems that combine robotic repeatability with real-time perception. Experiences from Mexico further reinforce the relevance of this solution in high-mix production settings, where balancing human supervision and robotic consistency is critical for maintaining productivity and quality.

Overall, this case study demonstrates how real-time sensing and closed-loop control can translate expert welding practices into repeatable, scalable robotic operations, improving

quality stability, enhancing safety, and enabling broader deployment across diverse fabrication environments.



Figure 14. Welding weave path laser tracking

3.2 Simulation-Based AI Path Optimization for Pick-and-Place Operations

The simulation-based AI path optimization case study corresponds strongly with shared implementation experiences from Japan;Singapore;Chinese Taipei; and Viet Nam, where digital modeling, virtual validation, and risk-aware deployment are increasingly adopted to improve operational reliability. The use of high-fidelity simulation environments to evaluate collision risk, clearance margins, and path efficiency before physical execution reduces commissioning time and minimizes disruption in human–robot collaborative settings.

In environments where robots operate alongside human workers, the ability to validate trajectories virtually enhances predictability and safety. This approach reflects broader practices in advanced manufacturing and infrastructure-heavy settings, where simulation plays a central role in anticipating interaction risks and optimizing task execution. The case study illustrates how AI-driven optimization and simulation-to-execution workflows enable smoother transitions from planning to operation, particularly in handling, sorting, and pick-and-place tasks that require precision and adaptability.

By emphasizing virtual verification prior to deployment, this solution supports a shift away from trial-and-error commissioning toward more structured, data-driven control, enabling both mature and transitioning manufacturing systems to achieve higher levels of stability and scalability.

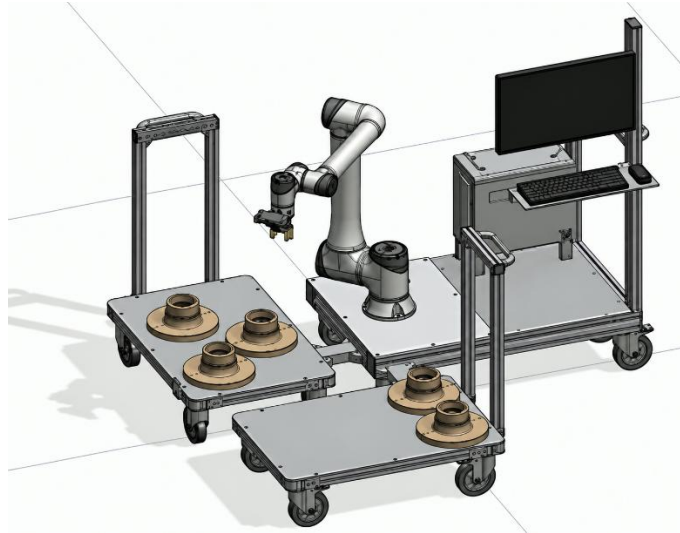


Figure 15. Simulation-Based Validation

3.3 Efficient Handheld Laser Welding Solution

The efficient handheld laser welding solution reflects practical implementation experiences from Mexico; Chinese Taipei; the United States and Viet Nam, where flexibility, usability, and rapid adaptation are key determinants of successful human-machine collaboration. The solution combines the stability of a collaborative robot arm with the dexterity and adjustability of a handheld laser welding gun, allowing operators to respond quickly to changes in welding position, geometry, and process conditions.

In manufacturing environments with frequent variation and limited engineering resources, this hybrid configuration enables operators to engage directly with advanced welding technology without complex reprogramming. Experiences from the United States highlight the importance of operator-friendly system design in lowering onboarding time and encouraging sustained adoption, particularly among small and medium-sized enterprises. Mexico's focus on flexible automation in cost-sensitive, high-mix production environments further aligns with the system's ability to accommodate variation while maintaining efficiency.

For manufacturing systems transitioning from labor-dependent toward more architecture-based control, this solution provides a practical pathway to introduce automation incrementally while preserving human judgment and manual flexibility. It demonstrates how advanced welding capabilities can remain ergonomic, adaptable, and accessible across a wide range of industrial contexts.

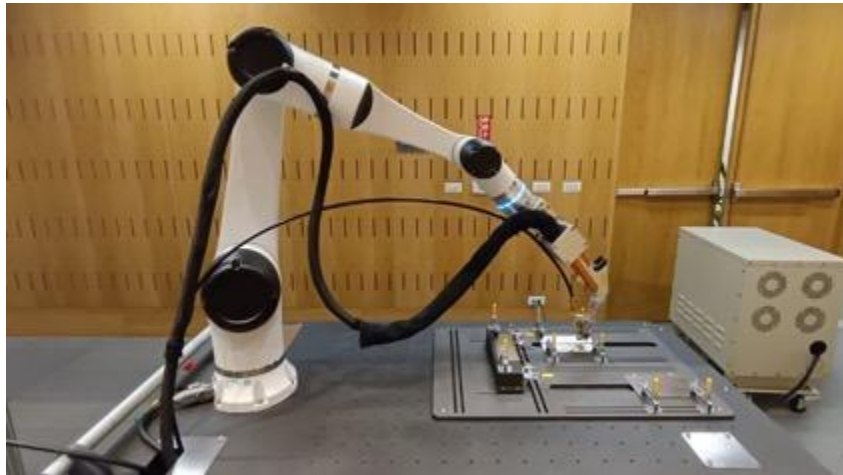


Figure 16. Efficient Handheld Laser Welding Solution.

4. Results and Analysis of Pre-Seminar Survey

4.1 Purpose and Objectives

The pre-seminar survey was designed to provide a foundational and evidence-based understanding of the current status, needs, and priorities related to smart human–machine collaboration (HMC) in the heavy steel construction industry across APEC economies. As an early-stage diagnostic tool, the survey serves to illuminate the varying levels of technological maturity among economies, highlight structural constraints that influence technology adoption, and clarify the industry’s readiness to integrate advanced automation into existing operational processes.

More specifically, the survey sought to:

1. **Identify key operational risks and structural challenges** that are shaping the demand for HMC technologies. This includes not only traditional concerns—such as safety hazards, workforce shortages, and production inefficiencies—but also emerging challenges related to digital transformation, aging infrastructure, and the rising complexity of heavy-industry projects.
2. **Assess existing mitigation measures and policy tools** currently implemented across economies. These may include regulatory frameworks, domestic industrial upgrading strategies, workforce development programs, and public–private initiatives aimed at accelerating digitization, automation, and industrial safety improvements.

3. **Map typical application scenarios and functional requirements** of HMC within real-world heavy steel environments. By understanding where HMC is already being applied—such as welding automation, structural assembly, pipeline installation, and real-time operational monitoring—the project aims to identify both common deployment patterns and sector-specific needs that require further innovation.
4. **Examine adoption drivers, cost sensitivities, and barriers** that influence industry decision-making. This includes factors such as return-on-investment expectations, integration challenges within legacy production systems, maintenance and lifecycle costs, technical support availability, and the role of organizational capabilities in enabling successful HMC deployment.
5. **Capture stakeholder perspectives on workforce development**, with particular emphasis on women’s participation and inclusive talent pathways. Recognizing that HMC technologies can reduce physical demands, enhance safety, and open new digital or supervisory roles, the survey aims to better understand how diverse and gender-inclusive talent pools can be supported as the industry transitions toward more automated and data-driven production models.

Collectively, these insights were used to shape the structure and thematic focus of the APEC workshop. The findings directly informed session topics, speaker selection, and capacity-building priorities—ensuring that the event is tailored to the actual challenges and opportunities identified by stakeholders across the APEC region. The survey results also guide the development of follow-up workstreams under PPSTI203_2024A, including knowledge-sharing activities, policy recommendations, and technical collaboration designed to support sustainable and inclusive industrial modernization.

4.2 Scope and Methodology

The survey was conducted online between December 2025 and January 2026, targeting a broad and diverse set of stakeholders across the heavy steel construction and smart human–machine collaboration (HMC) ecosystem. The respondent pool included industry practitioners, technology and system providers, research institutions, academic organizations, and manufacturers directly engaged in heavy steel fabrication, welding automation, robotics integration, and related HMC applications. Invitations were distributed through APEC PPSTI channels and the Metal Industries Research & Development Centre (MIRDC) to ensure participation from established communities of practice and practitioners with relevant domain expertise.

To capture both quantitative trends and qualitative insights, the survey employed a mixed-method questionnaire design.

- A mix of single-choice and multiple-choice questions was used to generate descriptive statistics covering key topics, including perceived industry risks, HMC functionality needs, deployment status, adoption drivers, and price sensitivity. For multiple-choice items, respondents could select more than one option, so aggregated percentages may exceed 100%. These structured responses enabled cross-economy comparison and identification of common patterns in industry readiness.
- Open-ended questions complemented the quantitative results by allowing respondents to elaborate on policy challenges, safety considerations, technical integration issues, maintenance burdens, and broader systemic barriers affecting HMC implementation. These narrative responses provided essential contextual depth and shed light on practical, on-site challenges that cannot be captured through fixed-choice formats alone.

This methodological approach ensured that the survey results reflected both the measurable dimensions of HMC adoption and the experiential knowledge of practitioners operating within complex industrial environments. The findings generated from the survey serve as a foundational input for shaping the design, thematic focus, and session priorities of the upcoming APEC workshop. Additionally, the insights will guide the development of subsequent capacity-building workstreams, including policy dialogue, technical knowledge exchange, and cross-economy collaboration under project PPSTI 203_2024A.

4.3 Result Analysis

4.3.1 Demographic Information

A total of 33 valid responses were collected through the survey, representing participation from a range of APEC economies as well as a small number of non-APEC economies. Based on respondents' selections in Q3.7 (APEC Economy You Represented), participants were from Indonesia; Japan; Malaysia; Mexico;; Singapore; Chinese Taipei; Thailand; the United States; and Viet Nam, with several responses categorized as Others, including Portugal and Benelux. Responses from non-APEC economies were included for reference only and to enrich comparative insights; analysis and policy implications primarily focus on APEC economies.

The respondent distribution shows a strong concentration of participation from Chinese Taipei, alongside contributions from multiple Southeast Asian, Northeast Asian, and American economies. This pattern reflects a geographically diverse engagement profile and indicates robust regional—and in some cases international—interest in advancing Human–

Machine Collaboration (HMC) within the heavy steel construction and fabrication sector. Given the sample size and the concentration of responses in specific economies, the findings should be interpreted as indicative rather than statistically representative of all APEC economies.

Table 1. List of Respondents by Economy (n = 33)

Economy	Count (n)	Share (%)
Indonesia	1	3.0%
Japan	2	6.1%
Malaysia	2	6.1%
Mexico	1	3.0%
Singapore	2	6.1%
Chinese Taipei	17	51.5%
Thailand	2	6.1%
United States	1	3.0%
Viet Nam	1	3.0%
Others	3	9.1%

Respondents represented industry, technology providers, and academic/research organizations, holding roles such as R&D leaders, program managers, robotics engineers, welding engineers, product managers, and professors. This distribution highlights the cross-disciplinary collaboration essential to scaling Human–Machine Collaboration (HMC) across the heavy steel construction ecosystem.

(1). Technology and system providers (52%)

Over half of the respondents came from robotics, welding automation, and digital system solution companies. Their positions—such as R&D leaders, product managers, and innovation officers—underscore the central role of solution developers in advancing HMC deployment in the region.

(2). Industry and manufacturing companies (33%)

One-third of respondents work in heavy steel fabrication, shipbuilding, and steel structure manufacturing. These industry representatives contributed insights on practical factory-floor challenges and operational requirements, offering an indispensable perspective on real-world deployment barriers and opportunities.

(3). Academic and research institutions (15%)

A smaller yet significant share of respondents came from universities and research institutions. Professors, researchers, and division heads provided expertise in advanced

manufacturing, welding science, robotics, and human–robot interaction, enriching the survey with scientific and forward-looking viewpoints.

The combined presence of these three stakeholder groups ensures a balanced multi-sector representation, allowing the survey results to capture technological, operational, and scientific dimensions of HMC development.

Table 2. Respondents by Organization Category (n = 33)

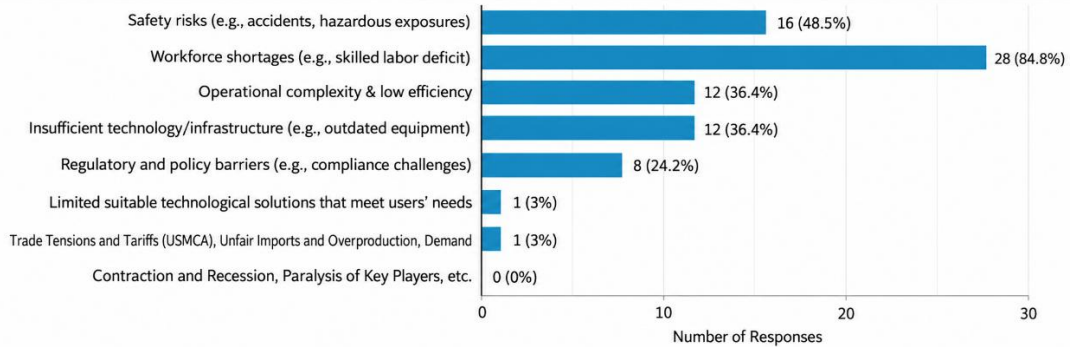
Organization Category	Count (n)	Share (%)
Technology and system providers	17	52%
Industry and manufacturing companies	11	33%
Academic and research institutions	5	15%

4.3.2. Policy and Regulatory Environment for HMC in Heavy Steel

Survey responses concerning economy-level attention to Human–Machine Collaboration (HMC) and the measures taken to mitigate sectoral risks (Q1.1, Q1.2) indicate a clear policy direction across the economies represented. The most prominent risk reported by respondents is the shortage of skilled labor, identified by 84.8% of participants, reflecting broader workforce aging, declining availability of trained welders, and persistent challenges in technical knowledge transfer. The second most frequently cited concern is safety risks, acknowledged by 48.5% of respondents, underscoring the inherently hazardous environments associated with welding, lifting, and structural assembly operations. Operational complexity and low efficiency were identified by 36.4% of respondents, illustrating the heavy reliance on manual processes and the resulting variability in productivity and quality. Additionally, 36.4% of respondents pointed to insufficient technology and outdated infrastructure as constraints that impede the adoption of modern industrial systems. Together, these percentages demonstrate that the heavy steel sector faces a combination of human-resource, operational, and technological pressures that strongly motivate the shift toward HMC.

Table 3. Primary risks in heavy steel industry

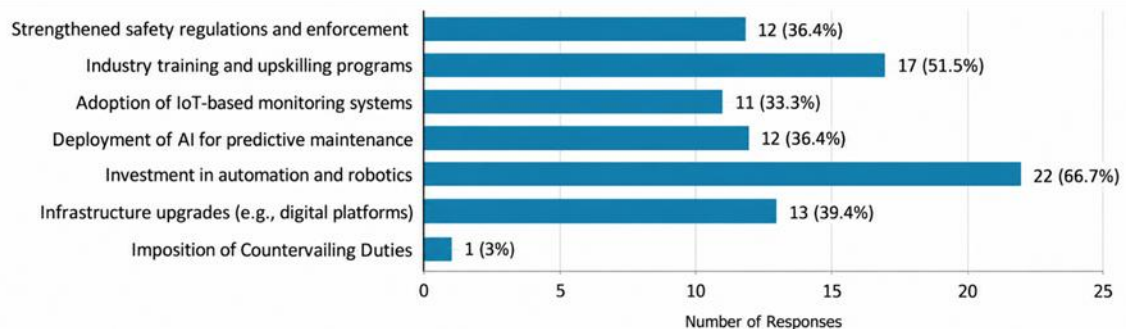
1.1 What are the primary risks the heavy steel industry currently facing in your economy?
Please select all that apply.



In response to these challenges (Q1.2), economies are prioritizing investment in automation and robotics, with 66.7% of respondents indicating that such investments constitute a key policy response. This includes deployment of collaborative robots, automated welding systems, and digitally monitored fabrication environments. Industry training and upskilling programs were selected by 51.5% of respondents, reflecting the recognition that workforce development is essential for supporting automation-driven industrial transformation. Infrastructure upgrades, particularly in digital platforms and modernized equipment, were noted by 39.4% of respondents as an important avenue for strengthening organizational readiness for HMC adoption. Meanwhile, strengthened safety regulations and AI-enabled predictive maintenance, each cited by 36.4% of respondents, represent complementary policy measures aimed at enhancing compliance, improving risk management, and leveraging intelligent systems to reduce unplanned downtime. These combined measures illustrate a broad regional policy trajectory that integrates technological modernization, skills development, and enhanced safety governance.

Table 4. Risk Mitigation Measures Implemented

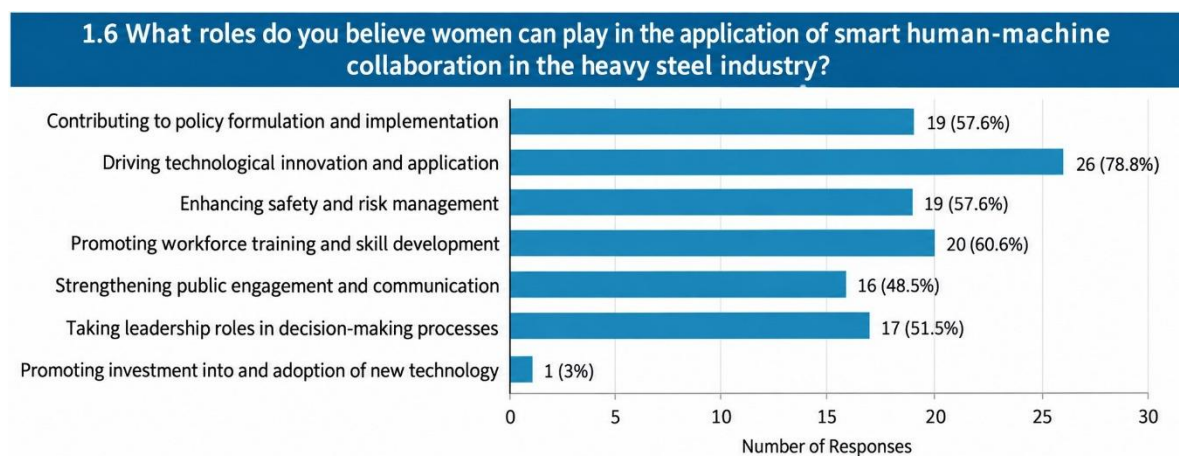
1.2 In your economy, which of the following measures are being implemented to mitigate the risks identified below?



Survey feedback on the roles of women and diverse talent in advancing HMC (Q1.6) further reflects an evolving policy environment oriented toward inclusiveness and human-centric industrial transformation. Respondents overwhelmingly indicated that women contribute substantially to technological innovation and application, with 78.8% selecting

this option. Workforce training and skill development was identified by 60.6% of respondents, reinforcing the link between talent diversity and effective capacity building. Safety and risk management was identified by 57.6% of respondents as an area where women play meaningful roles, and an identical 57.6% recognized women’s contributions to policy formulation and implementation. Leadership roles in decision-making processes were cited by 51.5%, while 48.5% highlighted women’s role in strengthening public engagement and communication. These percentages highlight a collective view that inclusive workforce strategies not only diversify the talent base but also strengthen the institutional capacity needed for a successful shift toward HMC. They also align with APEC’s broader agenda of promoting gender equality and inclusive participation in science, technology, and innovation.

Table 5. Roles of Women in HMC

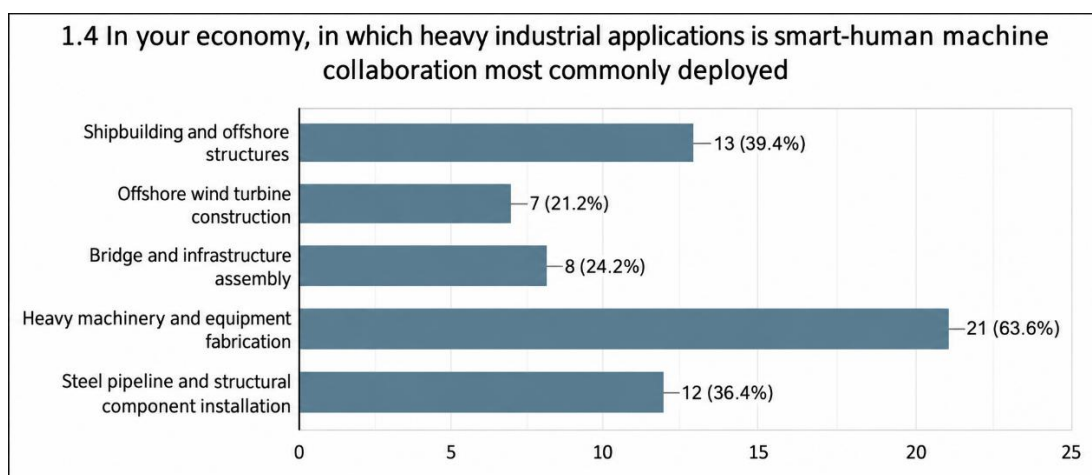


Taken together, the results reveal an emerging policy landscape in which economies recognize the structural risks confronting the heavy steel sector and are responding with integrated strategies that combine automation investment, workforce upgrading, infrastructure modernization, enhanced safety frameworks, and inclusive talent pathways. The consistent patterns across the percentages reported demonstrate that HMC has become both a technological solution and a policy priority for addressing long-standing challenges in productivity, safety, and workforce sustainability.

4.3.3 Current Deployment and Application Scenarios of HMC

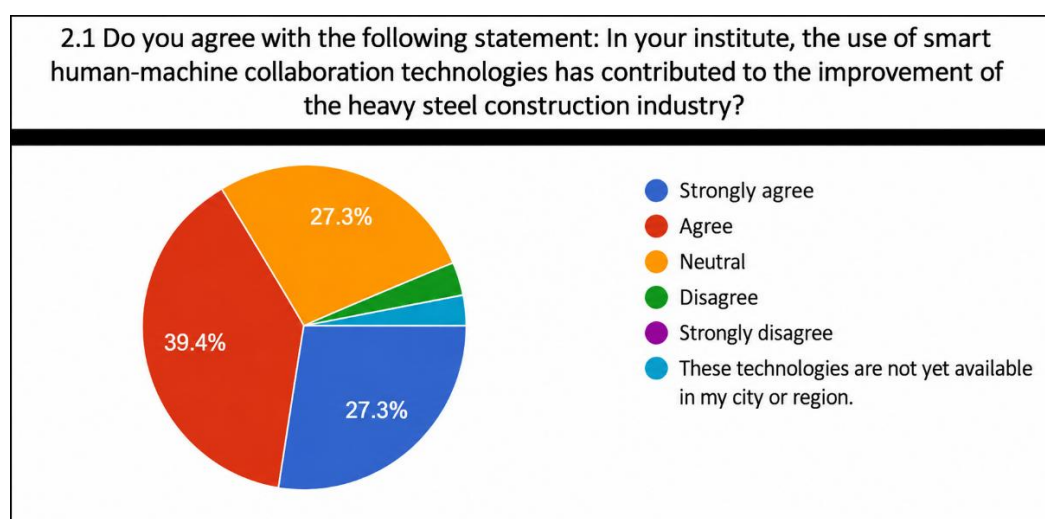
Survey findings indicate that HMC is most commonly deployed in heavy machinery and equipment fabrication (63.6%), shipbuilding and offshore structures (39.4%), steel pipeline and structural component installation (36.4%), and bridge and infrastructure assembly (24.2%) (Q1.4). These applications reflect the industry’s focus on high-impact, high-risk, and repetitive tasks where automation can stabilize quality and improve efficiency.

Table 6. Common Deployment Applications of HMC



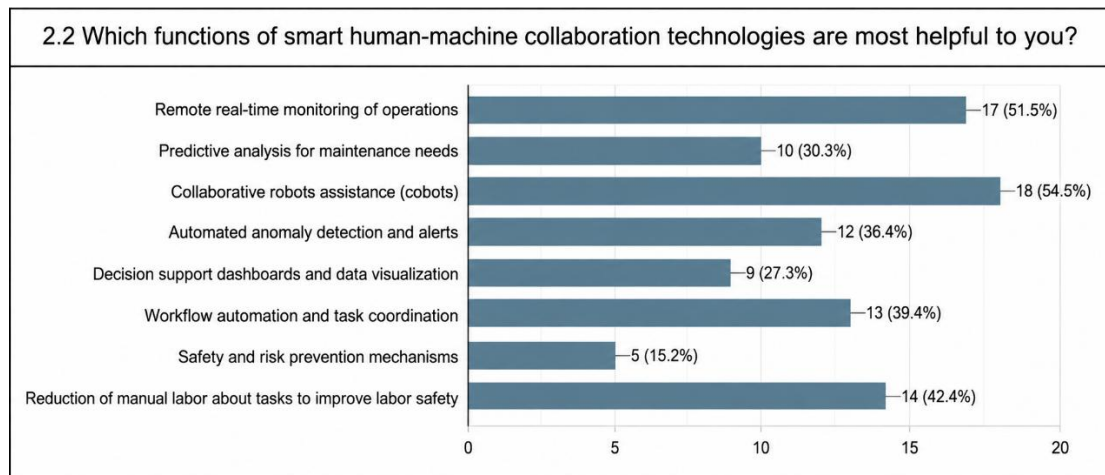
Regarding industry perception (Q2.1), responses show that the majority of participants agreed (39.4%) that HMC has contributed to improvements in the heavy steel construction industry, 27.3% strongly agreed. At the same time, 27.3% remained neutral, with smaller shares expressing disagreement (notably from Hong Kong, China) or noting that such technologies are not yet available in their city or region (as reported by Singapore). This distribution suggests that recognition of HMC's benefits is emerging, but adoption and impact remain uneven—largely due to differences in industrial structures and sectoral relevance.

Chart 1. Perception of HMC Contribution



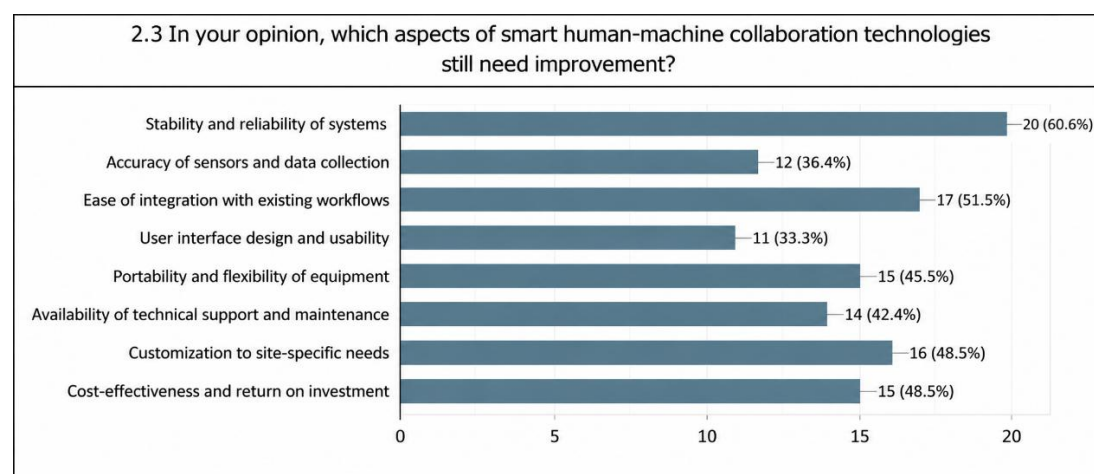
The functions most valued by respondents include collaborative robotic assistance (72.7%), remote real-time monitoring (57.6%), and reduction of manual hazardous tasks to improve worker safety (51.5%), followed by automated anomaly detection (51.5%) and workflow automation (45.5%) (Q2.2). These highlight the importance of technologies that directly enhance safety and operational reliability.

Table 6. Most Helpful HMC Functions



Areas identified as needing improvement were led by stability and reliability of systems (60.6%), ease of integration with existing workflows (51.5%), and customization to site-specific needs (48.5%). Other concerns included cost-effectiveness and return on investment (45.5%), portability and flexibility (45.5%), availability of technical support (42.4%), and accuracy of sensors and usability of interfaces (36.4%) (Q2.3). These priorities underscore the need for open interfaces, interoperability, and field-readiness to ensure sustainable deployment and lower long-term operating costs.

Table 7. Aspects of HMC Needing Improvement



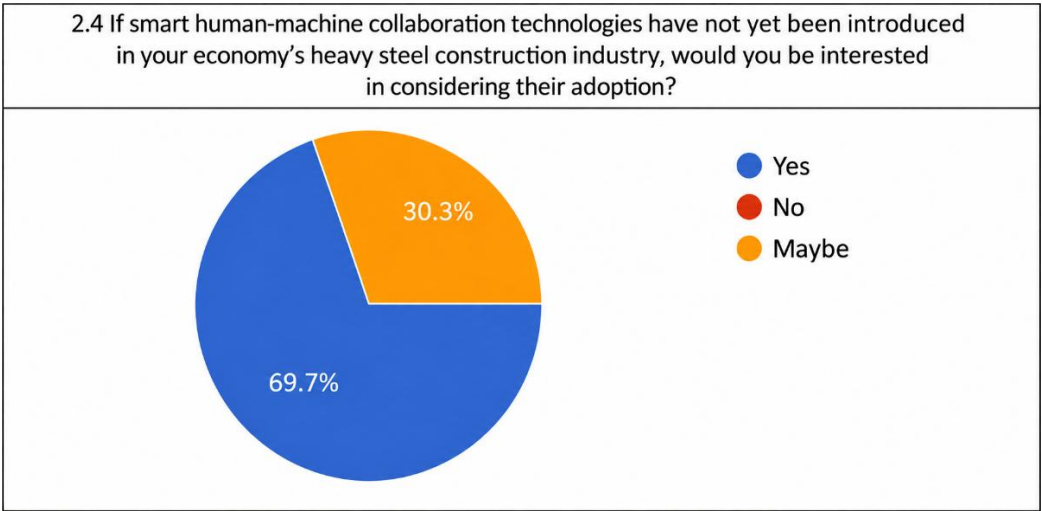
To sum up, HMC is most visibly applied in heavy machinery fabrication, with broad recognition of its benefits across most economies. Divergent views—such as disagreement in Hong Kong, China and non-applicability in Singapore—stem from differences in

industrial structures and sectoral relevance. Respondents value collaborative robotics, remote monitoring, and safety-enhancing automation, but emphasize the need to improve reliability, integration, customization, and cost-effectiveness. This shows that while HMC is seen as a transformative tool for safety and efficiency, its impact varies according to the industrial base and operational demands of each economy.

4.3.4 Technology Adoption, Cost Sensitivity, and Investment Considerations

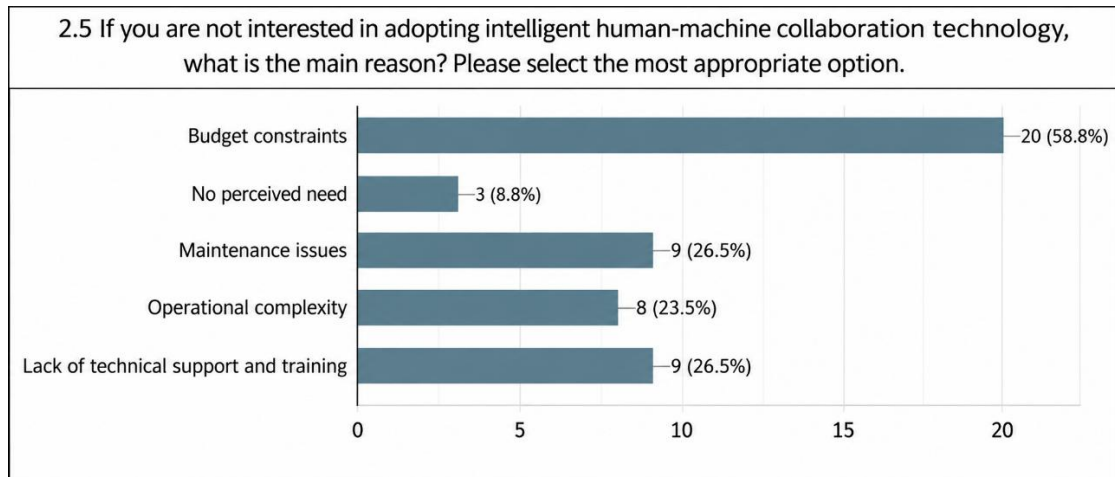
For respondents whose economies or institutions have not yet introduced HMC technologies, a clear majority expressed interest in future adoption (69.7%), while 30.3% indicated “maybe” and none rejected adoption outright (Q2.4).

Chart 2. Interest in Future Adoption of HMC



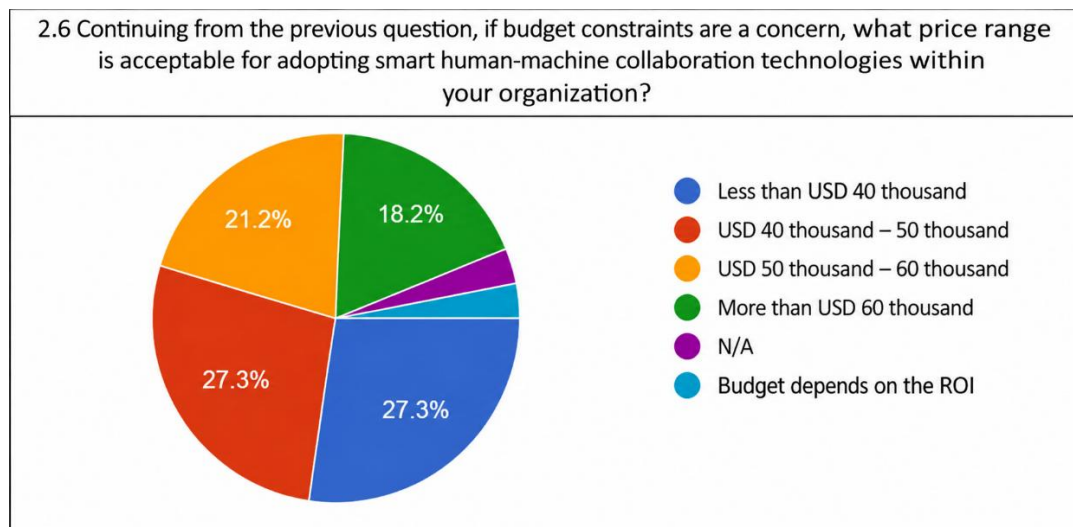
The most significant barriers identified were budget constraints (60.6%), followed by operational complexity (33.3%), lack of technical support and training (33.3%), and maintenance issues (30.3%). Only 9.1% cited no perceived need (Q2.5). These findings highlight that cost and integration challenges remain the primary concerns for wider deployment.

Table 8. Main Barriers to Adoption



Price sensitivity data further show that acceptable investment levels vary: 27.3% preferred solutions below USD 40,000, another 27.3% accepted USD 40,000–50,000, 21.2% USD 50,000–60,000, and 18.2% were willing to pay above USD 60,000. Smaller shares noted “N/A” or that budgets depend on ROI (Q2.6). This distribution underscores that affordability and demonstrable returns are critical to accelerating adoption.

Chart 3. Acceptable Price Range for HMC



Overall, the survey indicates strong interest in adopting HMC technologies, but financial feasibility and practical integration remain decisive factors. Economies and institutions are willing to explore adoption, provided that solutions are cost-effective, supported by training, and clearly demonstrate value in operational performance.

4.4 Key Findings and Conclusions

Survey findings from multiple economies—including Indonesia; Japan; Malaysia Mexico; ;Singapore; Chinese Taipei; Thailand; the United States; and Viet Nam—

consistently show that Smart Human–Machine Collaboration (HMC) is recognized as a strategic response to persistent structural challenges.

Specifically, respondents consistently identified workforce shortages—reflecting broader workforce aging, declining availability of trained welders, and persistent challenges in technical knowledge transfer—and safety risks as the primary issues driving the need for HMC adoption. Operational complexity and insufficient technology or outdated infrastructure further highlight why HMC is transitioning toward a pragmatic and scalable industrial approach.

The survey indicates that HMC delivers the greatest value when deployed in areas like heavy machinery and equipment fabrication, shipbuilding and offshore structures, steel pipeline and structural component installation, and bridge and infrastructure assembly. In these high-impact applications, HMC addresses repetitive and hazardous tasks by stabilizing quality and improving overall efficiency.

On the technological side, respondents show a clear preference for practical, human-centric collaborative systems. Survey respondents highlighted that the most helpful functions of HMC include collaborative robotic assistance (cobots), remote real-time monitoring of operations, and the reduction of manual hazardous tasks to directly improve worker safety, along with automated anomaly detection and workflow automation. To address industry risks effectively, economies are prioritizing broader investments in automation and robotics, industry training and upskilling programs, and infrastructure upgrades, alongside strengthened safety regulations and the deployment of AI for predictive maintenance.

Integration quality, system stability, and reliable technical support emerge as essential conditions for scalable HMC deployment. While there is strong interest in future adoption among those who have not yet implemented HMC, significant barriers remain. The survey identified that the stability and reliability of systems, ease of integration with existing workflows, and customization to site-specific needs are the primary aspects currently needing improvement.

On the investment side, budget constraints and operational complexity—followed by insufficient technical support and training—are the leading barriers to wider deployment. Most stakeholders show a preference for solutions within lower price tiers or emphasize that affordability and demonstrable returns are critical to accelerating adoption.

The survey also highlights HMC’s significant contribution to inclusive workforce development. Respondents emphasized that women and diverse talent play meaningful

roles in the application of smart HMC by driving technological innovation and application, promoting workforce training and skill development, enhancing safety and risk management, contributing to policy formulation, and taking leadership roles in decision-making. By fostering human-centric pathways, inclusive workforce strategies diversify the talent base and strengthen the institutional capacity needed for a successful shift toward HMC.

The survey insights demonstrate that Smart Human–Machine Collaboration represents a practical and resilient pathway for addressing longstanding challenges in productivity, safety, and workforce sustainability in heavy steel fabrication. Its success depends on resolving integration and reliability challenges, ensuring cost-effectiveness, and prioritizing human capital development. As economies continue to pursue sustainable industrial upgrading, HMC provides a shared framework for simultaneously advancing productivity, safety, and inclusive growth.

5. Policy Recommendations

From the perspectives shared during the workshop, a common understanding emerged that successful adoption of robotics, AI, and smart manufacturing within the APEC region depends not only on advanced technologies, but also on policy frameworks that support practical implementation, human-centered design, and long-term capability building. The following policy recommendations consolidate these insights into actionable directions for economies aiming to enhance productivity, resilience, and inclusive growth through smart human–machine collaboration.

- **Promote phased and practical adoption pathways for SMEs.**

APEC economies should encourage a step-by-step approach that allows small and medium-sized enterprises to begin with accessible technologies, such as collaborative robots or basic digital connectivity, before progressing toward more complex AI-driven systems. This reduces adoption risks, lowers entry barriers, and improves the likelihood of sustained implementation.

- **Strengthen local system integration and implementation capacity.**

Policies should prioritize the development of local system integrators and solution providers through targeted training, certification, and regional collaboration. Building domestic integration expertise is essential to ensure that technologies are effectively deployed, maintained, and adapted to local industrial conditions.

- **Embed usability and human-centered design as policy priorities.**

Smart manufacturing initiatives should place strong emphasis on usability, safety, and intuitive operation. By integrating human rights-centered design requirements

into public procurement, funding programs, and technical guidelines, economies can ensure that frontline operators are empowered to use and improve systems independently.

- **Invest in workforce development alongside automation adoption.**

Automation and AI should be positioned as tools that augment human capabilities rather than replace workers. Policies should support reskilling, knowledge transfer, and worker participation in automation projects, including mechanisms to preserve expert know-how and address workforce aging challenges.

- **Enhance regional cooperation on data, infrastructure, and standards.**

Given shared challenges related to data availability, computing resources, system reliability, and interoperability, APEC economies should collaborate on reference architectures, open standards, and aligned investments in digital and energy infrastructure. Such cooperation will reduce costs, improve compatibility, and support sustainable, inclusive innovation across the region.

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