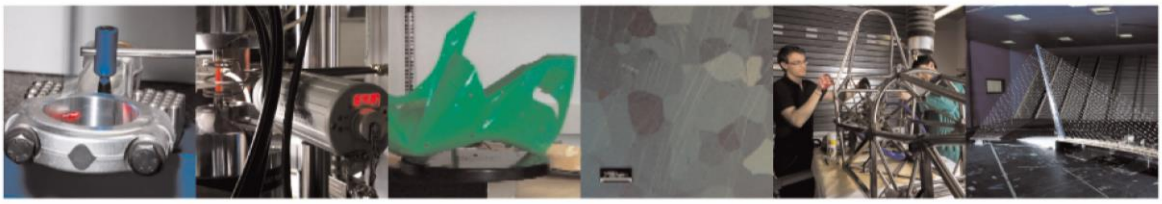

Rapid deployment of remote laser welding processes in automotive assembly systems

Ceglarek, Dariusz; Colledani, Marcello; Váncza, József; Kim, Duck Young; Marine, Charles; Kogel Hollacher, Markus; Mistry, Anil; Bolognese, Luca

This is a post-peer-review, pre-copyedit version of an article published in CIRP Annals. The final authenticated version is available online at: http://dx.doi.org/10.1016/j.cirp.2015.04.119

Rapid deployment of remote laser welding processes in automotive assembly systems

Dariusz Ceglarek (1)[a,*], Marcello Colledani (2)[b], József Váncza (1)[c,d], Duck-Young Kim[e], Charles Marine[f], Markus Kogel-Hollacher[g], Anil Mistry[h], Luca Bolognese[i]

[a] Digital Lifecycle Management (DLM), WMG, University of Warwick, Coventry CV4 7AL, UK
[b] Politecnico di Milano, Department of Mechanical Engineering, Via la Masa, 1, 20156 Milan, Italy
[c] Institute for Computer Science and Control, Hungarian Academy of Sciences, Budapest, Hungary
[d] Department of Manufacturing Science and Technology, Budapest University of Technology and Economics, Budapest, Hungary
[e] Ulsan National Institute of Science and Technology, Ulsan, South Korea
[f] Stadco Limited, Hortonwood, Telford, Shropshire TF1 7LL, UK
[g] Precitec Optronics GmbH, Neu-Isenburg, Germany
[h] Jaguar LandRover, Gaydon, UK
[i] COMAU, Grugliasco, Italy

1. Introduction, motivation and objectives

The development of sustainable manufacturing requires *key enabling technologies* (KETs) that can help industries to better understand and respond to economic, societal and environmental challenges [1]. This is especially important in the context of globalization. Indeed, globalization coupled with product customization and steadily decreasing time-to-market have spearheaded unprecedented levels of competition among manufacturers making high performance sustainable production an essential feature by which to address ever growing consumer demand for greater variety of goods and services [2]. At its core this means producing zero-defects products faster, better, and cheaper and accomplishing these by ensuring high rate of *right-first-time* [3].

Remote laser welding (RLW) is emerging as a powerful and promising joining technology (one of the KETs) in vehicle manufacturing. By having laser optics embedded into the robot (Fig. 1), and a scanning mirror head as the end-effector, RLW can easily create joints in different locations of the product through simple robot repositioning and/or laser beam redirection from a remote distance. In essence, RLW takes advantage of three main characteristics of laser welding: non-contact, single-sided joining technology, and high power beam capable of creating a joint in a fraction of a second. However, at present, there is lack of systematic methodologies for efficient application of RLW in automotive manufacturing processes thus preventing manufacturers from taking full advantage of the spectrum of benefits provided by RLW. For example, RLW process design and control are based on very time-intensive and sub-par trial-and-error approach making its application extremely limited in automotive assembly processes. At the same time, simply replacing RSW with RLW is infeasible, thereby necessitating the design of a new assembly line with selected RLW cells and then, validation of its effectiveness such that RLW can be methodically integrated into the existing production system. In order to address the above challenge, this paper presents a '*Push–Pull*' KETs framework for rapid deployment of the '*Push*' KET (RLW technology) in a new assembly system by developing necessary '*Pull*'

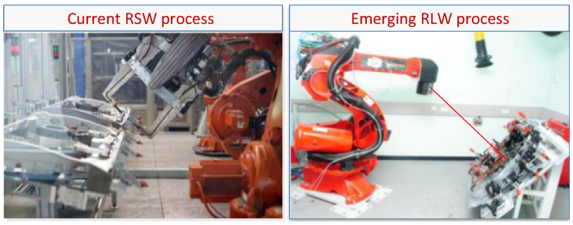

Fig. 1. Resistant spot welding (RSW) vs. remote laser welding (RLW).

* Corresponding author.
E-mail address: d.j.ceglarek@warwick.ac.uk (D. Ceglarek).

KETs (portfolio of simulation and optimization tools) (Fig. 2). '*Push*' KETs are seen as new technology, i.e., RLW process, with potential benefits, if successfully applied, in manufacturing systems. On the other hand '*Pull*' KETs can be defined as methods necessary to '*Pull*' the '*Push*' KET into a new assembly system to realize its full benefits (Fig. 2). The proposed '*Push*'–'*Pull*' framework is necessary for the rapid deployment of new technology into a manufacturing system. This paper presents a portfolio of '*Pull*' KETs that have been developed and integrated into the RLW Navigator system to help industries take full advantage of deploying the RLW process [4].

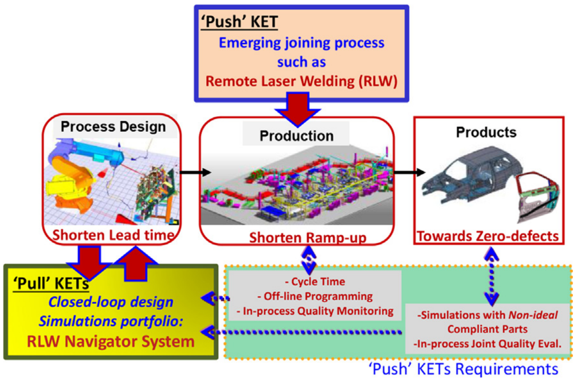

Fig. 2. Framework for rapid deployment of RLW process.

2. RLW Navigator framework

As a portfolio of '*Pull*' KETs, the RLW Navigator provides necessary analytics for rapid deployment of RLW during new assembly process development. The RLW Navigator is based on a *hierarchical decomposition* of manufacturing system which includes the following modules together with their KETs and the flow of information as also shown in Fig. 3: (1) *System design* embeds RLW technology in the fabric of complete production systems. (2) *Workstation planning* determines the detailed configuration of an RLW workstation and its operation, up to off-line programming (OLP). (3) *Process design* sees that all technological constraints are satisfied by appropriate fixture layout and process parameters. (4) *Process control* performs in-process quality monitoring and adjustment of the main process parameters so as to produce joints of required quality.

The modules have their own internal decision mechanisms which make use of the appropriate KETs typically in an iterative manner (see intra-loops in Fig. 3). The modules are briefly presented below, but note should also be made of their interplay denoted as *inter-loops*. In the *system configurator* inter-loop set of welding tasks, cycle time and selected resources (primarily, the RLW robot) are consolidated: While the *system design* module can make decisions about these key variables based on estimates only, the *workstation planning* module can verify whether and how these high-level decisions can be aligned with each other in light of the detailed configuration and operation plan of a workstation. Similarly, in the *station configurator* inter-loop the key technological decisions are refined, specifically for fixture and welding parameters selection and optimization. While these tasks form part of the *process design* module, fixture layout has to be assessed in terms of accessibility which is a core competence of the *workstation planning* module.

3. '*Pull*' key enabling technologies (KETs)

3.1. System design module

The goal of the *system design* module is to support the rapid early-stage design of the assembly system and to properly integrate RLW stations in the system, thus allowing to fully exploit the potentials of RLW. This module is also the first interface with the system designer. As shown in Fig. 3, the input data for this module are as follows: (i) production models and product related information, including stitch layout; (ii) target production volumes and throughput; (iii) database of resources, with their nominal reliability parameters, process capabilities, space and cost requirements; and, (iv) basic operational cost factors (e.g. workforce, maintenance, floor space costs).

Grounding on these input data, the *system design* module analyzes system configurations to achieve a minimum requirement on throughput while minimizing multiple objectives including the number of resources (buffers and robots), costs, energy, and floor space. The main outputs of this module consist of the: (i) layout concept; (ii) basic concept and contents of the RLW workstation, number of robots, robot model, and workload (set of stitches); (iii) maximum value of CT_{RLW}, i.e., total time the RLW station requires to process one part that can ensure process feasibility in terms of productivity requirements, also considering machines' reliability; (iv) optimal buffer sizes and the key performance indicators (KPIs) of the evaluated configurations. This then feeds into the *workstation planning* module.

The above is achieved within the *system design* module intra-loop by two interacting sub-modules, namely *process estimator* and *system analyzer*. With the first sub-module, the designer interacts with the software platform through a customized graphical user interface (GUI) to populate the system with manufacturing resources, selected from a pre-defined component database, thus generating an initial assembly line configuration and layout. In the same sub-module, the user can define and visualize an initial task sequencing. It is possible to cluster all resources performing homogeneous sets of operations into stations. The *process estimator* sub-module calculates some basic system KPIs. Once the initial configuration has been generated, all the related reliability data are automatically retrieved from a reliability database. The station models, as well as the system topology to be optimized, are provided as input to the *system analyzer* sub-module by means of so-called *transfer functions*. Next, the *system analyzer* sub-module tests several alternative system configurations before implementation, by exploiting the features of a fast performance evaluation module [6], based on approximate analytical methods. Upon convergence of the selected optimization algorithm, the set of candidate Pareto-optimal configurations are visualized to the designer. In addition, it is possible to further perform post-processing on the candidate solutions, via robustness analysis and discrete event simulation. The control of the flow of information between these sub-modules and the optimization is performed by a workflow implemented within the commercial software platform modeFRONTIER 4.5 (ESTECO).

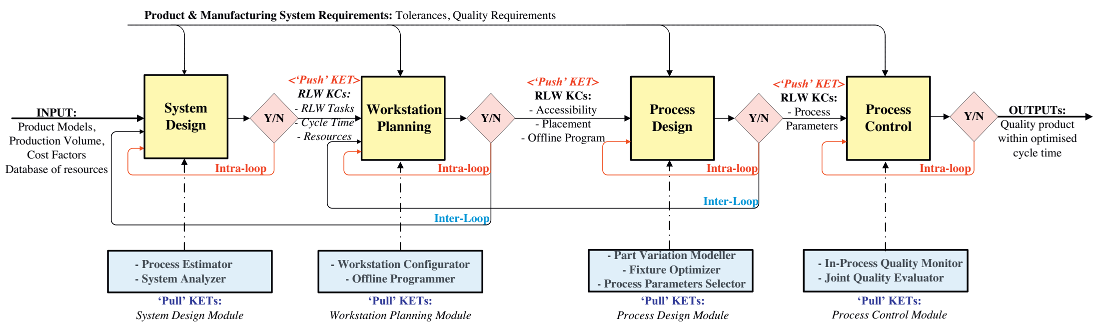

Fig. 3. Framework of the '*Pull*' KETs for rapid deployment of RLW process ('*Push*' KET).

This software supports multi-objective optimization and integration between multi-domain software modules.

The *system design* module features relevant innovations with respect to existing approaches based on the automatic generation of system design options and simulation-based optimization [5]. It provides designers an ability to control and manage the process in each design phase, thus avoiding the generation of black-box solutions. Within this platform more than 1500 potential user-driven configurations can be investigated in less than 20 min, thus drastically reducing early stage design time.

3.2. Workstation planning module

The *workstation planning* module is responsible for determining the detailed configuration and operation of an RLW workstation. It works with the following inputs: (i) set of welding tasks – together with the selected resources and their layout pattern including the model of the RLW robot, and the upper limit of the cycle time of the workstation (from *system design* module); (ii) CAD model of the product and a refined version of the welding fixture (from *process design* module). Initially, only the clamp layout is given, though later stages include the CAD model of the fixture; and (iii) for each welding task, the specification of process parameters, i.e., welding power and speed, and maximal inclination angle of the laser beam (from *process design* module).

The generated outputs include: (i) accessibility analysis of the welding tasks; (ii) detailed configuration of the workstation, with the precise placement of all its elements; (iii) executable off-line program of the robot that completes the given set of welding tasks with a minimal CT_{RLW} cycle time; and (iv) simulation of the operation of the workstation. The executable OLP should comply with the kinematic model and the controller of the robot, satisfy all the technological constraints of RLW, allow the laser beam to be directed on stitches only, and avoid any collisions.

The solution of the above problem rests on new models and KETs that are integrated into a common *workflow*. First, located in the Cartesian coordinate system of the part, so-called *technological access volumes* (TAV_i) are used for each i stitch to represent the area of space from where the stitch can be welded within the limits of its specific technological parameters (Fig. 4). Subsequent analysis may reduce any initial TAV_i so as to avoid the collision of the beam and the fixture, as well as the scanner head and the fixture or the part. Second, the complete workstation is represented in a single generic *linkage mechanism* which includes not only the robot and the mirror apparatus controlling the laser beam, but also every object within the boundaries of the cell. Initially, the linkage is defined in terms of the input data, while as proceeding along the workflow it evolves through a hierarchical refinement process. Hence, additional details such as TAVs, accessibility indices, robot scanner path, fixture and part placement, robot motion plan and executable code are added to the linkage. Since the process involves engineering interaction, the linkage-based representation is also supported by appropriate visual presentation.

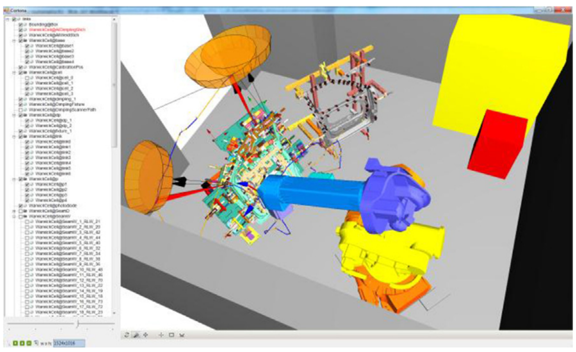

Fig. 4. A completely specified RLW workcell, including a dimpling and a welding fixture.

The workflow accounts both for the static and dynamic aspects of the core problem: configuration and planning decisions are made hand in hand by taking geometrical, kinematic and technological constraints into consideration. First, *accessibility analysis* checks whether all the welding (or dimpling) tasks are accessible by the laser beam given the part, fixture and robot geometries, and welding parameters. In case of no or restricted accessibility, feedback to *process design* is provided. Next, *task sequencing and path planning* generates a collision-free path for the scanner head with the shortest possible cycle time. Here, a new method has been developed that looks for a close-to-optimal path leading through the *TAVs* by tackling task sequencing and path planning in an integrated way [7]. If the CT_{RLW} cycle time exceeds the upper limit given by the *system design*, then either the set of tasks or the actual robot should be changed. Next, *placement* is responsible for finding a posture of the fixture and the part relative to the robot such that no collisions occur and the path of the scanner head to be included in the robot's workspace. If such a placement cannot be found, then the path is re-tailored, the specification of the fixture is modified, or, in the last resort, the set of tasks is changed. *Inverse kinematics* generates the motion plan for the joints of the robot, including the synchronized control of the laser beam, and *trajectory planning* adjusts the motion plan to the precise joint velocity and acceleration limits and generates the final path. *Off-line programming* transforms the motion plan into a robot program that is executable by its specific controller and, finally, *simulation* presents the operation of the entire RLW workstation. For a typical final result see Fig. 4.

The workflow was implemented in a single system that integrates services of the above KETs. Details of the workflow are presented elsewhere [7–10]. A number of computational experiments have shown that compared to the traditional method [11] the new path planning algorithm reduced the cycle time on average by 67%. This improvement was mainly due to optimizing the path of the scanner head, instead of the path of the tool centre point (i.e., where the beam hits the part). This configurator and OLP system was also applied in the physical experiments (Section 4).

3.3. Process design module

The main goal of the *process design* module is to optimize process performance to achieve optimum quality of the final RLW assembled product. Three main challenges have been identified: (i) *part-to-part gap control* – modelling sub-assembly fit-up considering single or batch of parts errors; (ii) *fixture layout optimization* – modelling and simulation of fixturing and tooling together with part deformation considering batch of non-ideal parts and sub-assemblies; and (iii) *selection of process parameters* – selecting optimum set-up of process parameters satisfying joint quality, productivity (i.e., welding speed), and energy demand (i.e., laser power) [12]. To tackle these challenges a systematic framework has been implemented (Fig. 3).

The quality of the joint is directly related to the part-to-part gap which is imputed to dimensional and geometric variation of stamped sheet-metal parts and to fixture location and tooling variations. Also, the joining process is affected by the laser beam visibility of all stitches, and weld quality is affected by the process parameters such as laser power, welding speed, and material stack-up. Three main sub-modules have been developed: (i) part variation modeller; (ii) fixture layout optimizer; and (iii) laser parameters optimizer. Product and process (CAD/CAM specs) data are used as input, and the following optimum outputs are obtained: (i) clamp layout; (ii) stitch layout; and (iii) laser parameters. If any infeasibility is detected (i.e., quality of some stitches cannot be achieved because of too large gap), then the product needs to be modified, typically by changing the stitch layout.

3.3.1. Part variation modeller

The tool generates virtual *non-ideal* part or assembly based on CAD data (including GD&T specs) and measurement data (i.e., cloud-of-points) [13–15]. It has the capability for: (i) variation simulation analysis of deformable sheet-metal parts; (ii) part error characterization for single part and batch of parts. The tool implements innovative methods to simulate "within batch" and "batch-to-batch" variation. The tool's integration capabilities are: (i) calculation of part fit-up to satisfy joint performance; (ii) definition and optimization of locator/clamp layout (if integrated with the *fixture layout optimizer*); and (iii) extract significant deformation patterns from high density cloud-of-points. Fig. 5 shows the tool's user interface with some snapshots of the calculated deformation patters of a door inner panel.

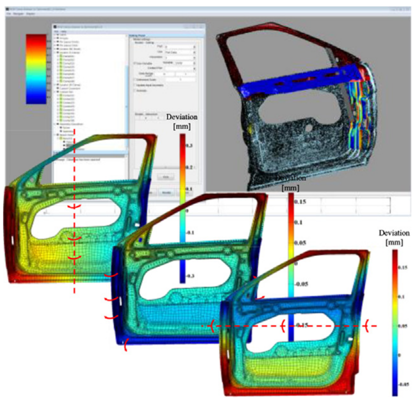

Fig. 5. Part variation modeller.

3.3.2. Fixture layout optimizer

The tool allows to model the impact of dimensional and geometrical variation, as generated by the *part variation modeller*, on process parameters (clamps layout). This implies that the fixture is optimized not only for a nominal CAD product but also for "real" non-ideal product, considering the batch-to-batch or within batch variation [16]. The main outcomes are: (i) foot-print of clamp layout (to be transferred to the mechanical design of the fixture) and; (ii) numerical evaluation of critical performance requirements, such as assembly deviation, reaction forces on the clamps/supports and/or elastic spring-back. This tool's integration capabilities are: (i) optimized product design loop to generate a feasible assembly process; (ii) optimum locator/clamp layout; (iii) joining process parameters' loop; (iv) workstation optimization loop with robot simulation and path planning. The fixture layout analyzer and optimizer can be used as interactive/collaborative framework among process and product design engineers. The developed GUI (Fig. 6) offers interactive tools to facilitate user's data input and visualization of results.

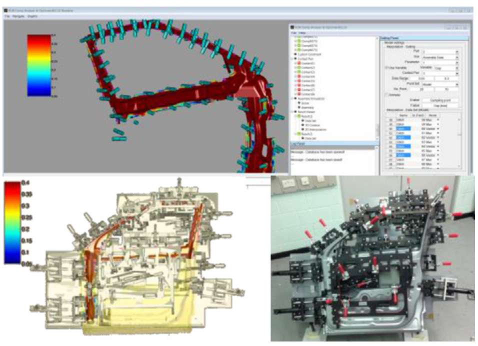

Fig. 6. Fixture layout optimizer.

3.3.3. Laser parameter optimizer

This tool allows to select and optimize joining process parameters (i.e., laser power, inclination angle and welding speed). It links, through response surface method, the input process parameters to the output joint performances, such as joint cross section, penetration, and interface width (Fig. 7). The analytical relation is obtained by combining physical experimentation and

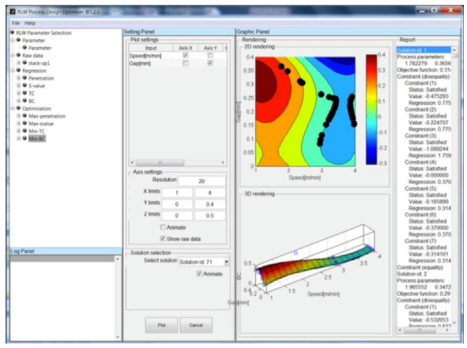

Fig. 7. Laser parameters optimizer and selector.

computer simulation [17]. Optimum parameter settings are then automatically calculated, depending on material stack-up combinations and performance constraints based on industry standards (i.e., joint strength, penetration or visual appearance).

3.4. Process control module

The main goal of the RLW *process control* module is to have in-process monitoring and simultaneous joint quality evaluation as measured by key joint quality indicators: penetration, *s*-value and top-concavity by using real-time and in-process data (e.g., plasma, temperature and back-radiation). The state-of-art solution to this problem assumes that the joint's quality can be inferred by comparing signal templates against the measured signal. Although this can be implemented in-process during welding, it is sensitive to interpretation and does not directly indicate quality of joints.

The developed tool extends the state-of-art by providing a novel approach [18] for linking in-line process monitoring signals with process KPIs. The tool involves two steps: (i) in-process radiation monitoring (i.e., using photodiode); and (ii) analytics correlating data to joint performance. To develop the analytical model the process signal is filtered into visible light, temperature and back-reflection using photodiode sensor. The filtered signal is then used to extract significant features, correlated to joint performance. Optimum process parameters are then calculated which satisfy cycle time (welding speed) or minimum power demand.

Successful experiments were done to link process signals to *s*-value (Fig. 8). Results show the possibility to: (i) perform in-process weld analysis thus reducing costly off-line and destructive tests; (ii) use of mathematical model automatically linking monitoring data to joint performance; (iii) facilitate statistical process control (SPC) and root cause analysis of joint failures; and (iv) perform in-process closed-loop process control and adjustment.

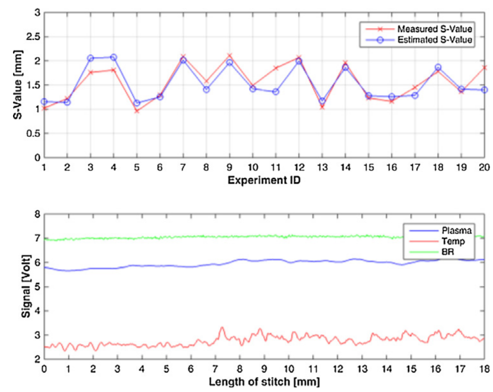

Fig. 8. In-line joint quality evaluation (i.e., *s*-value) using in-line monitoring signal (i.e., plasma, temperature and back-radiation).

4. Rapid deployment of '*Pull*' KETs

The individual KETs have been implemented as a set of software modules within the RLW Navigator system. Fig. 3 illustrates the inputs and outputs of each software module, their interactions and information flow. The software modules iteratively exchange their optimization results, design solutions and related KPIs, thus progressively updating the overall solution while at the same time keeping the coherence of the results provided by each software module. Overall, the developed '*Pull*' KETs allowed simulation and optimization of the RLW process upfront to minimize the challenges for system design, workstation configuration, welding process optimization and process control. Each module is engineered to support a specific activity of a new product introduction (NPI) process of a vehicle (Fig. 9), namely system design, workstation planning, and process design, during the engineering phase, as well as process control, after production tooling installation. This systematic coordination of software modules across different stages of NPI enable '*right-first-time*' solution capability, decreased commissioning time and cost, shorten design time, improved design results and robustness, and knowledge re-use, by which the overall NPI process will be accelerated. The RLW KETs provide better feasibility of the solution at order acquisition stage (A2–A1) and increase feasibility and time reduction (B2–B1) in the engineering and manufacturing stages. It shows the overall impact on launch time reduction (D2–D1) and early start of production as compared with the RSW process.

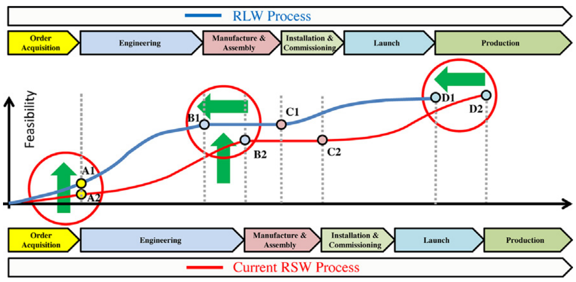

Fig. 9. Impact of simulation tools on new product introduction process.

5. Automotive door assembly pilot study: implementation of the RLW KETs deployment

The RLW Navigator approach – with all the KETs – has been validated and verified in an automotive pilot study that was aimed at the rapid deployment of the RLW technology in an automotive door assembly process. The set of products to be assembled in one RLW cell included both left- and right-hand front door assemblies that were assembled from a number of parts, such as door inner, reinforced door opening, hinge reinforcement, latch reinforcement, hinge plate, window channel, waist rail and impact beam. The pilot study involved system-level design and resulted in the successful physical build of a batch of optimized RLW doors. Results of the pilot are summarized below.

System design revealed that the RLW joining process has several benefits over RSW and self-pierce riveting (SPR) joining. Whereas the throughput of the overall system was intended to remain the same, the number of robots in the overall production system was reduced, specifically, 5 robots in the RLW cell have taken up the work of 14 robots in the RSW cell. Further, the floor space required for the production was reduced approximately by 50% (Fig. 10). Equally important, the estimated total energy demand per product decreased by 57%. Fig. 11 provides the cost comparison among the RLW, RSW and SPR joining methods. The cost components are mainly classified into two segments: (i) *investment costs*, including engineering, incoming services, hardware, quality control, and implementation costs; and, (ii) *operating and maintenance costs*, including floor space, service consumables, process consumables, spare parts, maintenance and quality. An

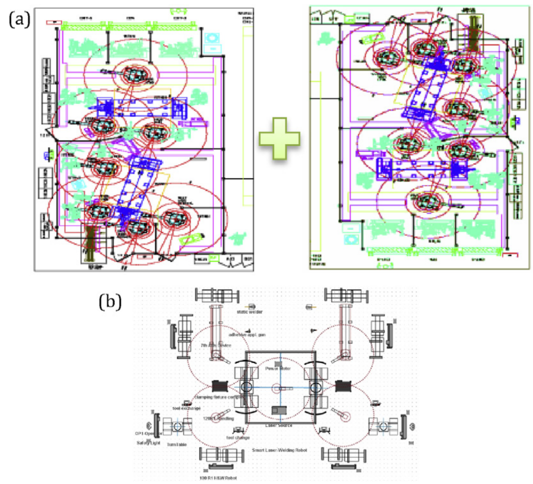

Fig. 10. Current sport utility vehicle: (a) RSW door assembly line for RH/LH front doors; and (b) the developed RLW cell for RH/LH doors.

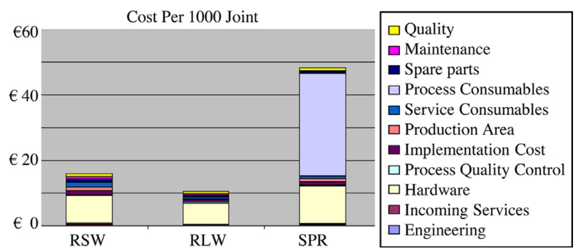

Fig. 11. Cost comparison between RSW, SPR and RLW processes.

equivalent RLW stitch costs 34% and 78% less than a RSW and SPR joints, respectively.

The *workstation planning* KETs have been used to design a detailed configuration of an RLW workstation that complies with all its technological and spatial constraints. Starting from the CAD models of the product and the fixture (that was built on the basis of the clamp layout generated by *process design*), the specification of dimpling and welding tasks, as well as the off-line robot program was generated for the COMAU C4G Smart Laser robot. The final result was achieved via an iterative improvement of the clamping conditions with *process design* which was facilitated by accessibility analysis and the detailed simulation of the complete RLW process (Fig. 12). Cycle time was reported to be 50% less than that given by industrial experts, and the generated code was directly executable in test production ('*right-first-time*').

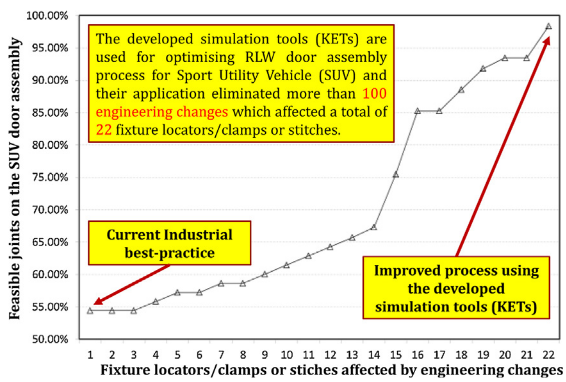

Fig. 12. Simulation and optimization based results of engineering changes to reach quality output.

Process design KETs helped to eliminate most of the engineering changes and adjustments that are typically required in real process development. Figs. 13 and 14 show examples of changes identified by the developed simulations which cannot be identified by current state-of-the-art approaches [19–25]. Altogether, almost

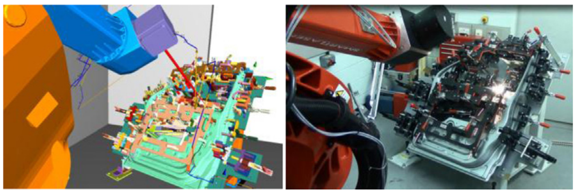

Fig. 13. RLW simulated and real door fixture.

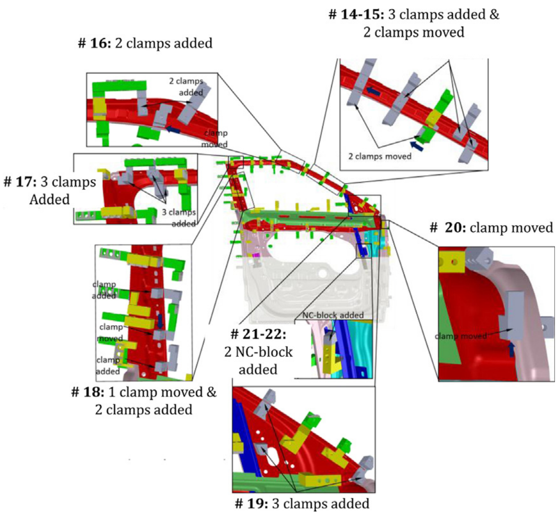

Fig. 14. Engineering changes.

one hundred modifications have been suggested on the original product and clamping model. All engineering changes could be implemented by using the appropriate simulation platforms that resulted in 98% joints achieving right-first-time quality. This is in sharp contrast with the current industrial practice which can reach up to 55% success during the equivalent design stage. Results of subsequent physical tests confirmed the correctness of the suggestions and the choice of process parameters.

Finally, *process control* KETs have been applied to evaluate joint quality by using in-process monitoring data instead of conducting destructive tests. According to the final comparative tests, there was a good agreement between predicted and measured KPIs in that for 80% of the stitches the prediction error was below 10%.

6. Conclusions

Remote laser welding (RLW) has attracted interest in the recent years due to its benefits in terms of process flexibility, speed and energy efficiency. However, the potentials of RLW in automotive assembly have been so far under exploited, mainly due to system and process design, part variation, fixturing, off-line programming, as well as process monitoring and control challenges. The paper proposed a rapid deployment framework for RLW processes and systems that addresses all the above issues in an integrated way. Accordingly, main modules of system design, workstation planning, process design and process control have been presented together with their key enabling technologies that apply a broad apparatus of mathematical modelling and simulation methods. Emphasis was on organizing the interaction of modules which is the key to arrive at consistent solutions on all levels that do not call for engineering changes at the time of realization. Inclusively, a closed-loop process monitoring and control method was developed for compensating the potential variation between ideal and real welding processes. The RLW Navigator framework was applied in a detailed automotive pilot study which yielded promising results. Findings corroborated the initial hypothesis on the necessity of a multidisciplinary approach for handling the complexities and subtle interactions of system, process and product related decisions when deploying RLW processes.

Acknowledgements

This study is partially supported by the European Research Project EU-FP7 FoF-ICT-2011.7.4: Remote Laser Welding System Navigator for Eco & Resilient Automotive Factories (#285051), the UK EPSRC EP/K019368/1: "Self-Resilient Reconfigurable Assembly Systems with In-process Quality Improvement", and by the Hungarian NFÜ grant No. ED_13-2-2013-0002.

References

[1] Ceglarek D (2014) Key Enabling Technologies (KETs) can 'Strengthen European Industry'. *The Parliament Magazine* 397:79–80. (invited article).

[2] ElMaraghy H, et al (2013) Product Variety Management. *CIRP Annals* 62(2): 629–652.

[3] Ceglarek D, et al (2004) Time-Based Competition in Manufacturing: Stream-of-Variation Analysis (SOVA) Methodology – Review. *International Journal of Flexible Manufacturing Systems* 16(1):11–44.

[4] Ceglarek D, Franciosa P, Váncza J, et al (2011) *Remote Laser Welding (RLW) System Navigator for Eco and Resilient Automotive Factories, FoF-ICT-2011.7, No. 285051*. URL: http://www.RLWnavigator.eu/.

[5] Michalos G, Makris S, Mourtzis D (2012) An Intelligent Search Algorithm-Based Method to Derive Assembly Line Design Alternatives. *International Journal of Computer Integrated Manufacturing* 25(3):211–229.

[6] Colledani M, Ratti A, Senanayake C (2014) An Approximate Analytical Method to Evaluate the Performance of Multi-Product Assembly Systems. *9th CIRP Confer-ence on Intelligent Computation in Manufacturing Engineering (ICME)*, Naples, Italy.

[7] Kovács A (2013) Task Sequencing for Remote Laser Welding in the Automotive Industry. *Proceedings of the 23rd International Conference on Automated Plan-ning and Scheduling (ICAPS-2013)*, 457–461.

[8] ErdősG,etal(2014)WorkstationConfiguration&ProcessPlanningforRLW Operations.*ProcediaCIRP*17:783–788.

[9] ErdősG,KardosC,KeményZ,KovácsA,VánczaJ(2015)ProcessPlanningand OfflineProgrammingforRoboticRemoteLaserWeldingSystems.*International JournalofComputerIntegratedManufacturing*.http://dx.doi.org/10.1080/ 0951192X.2015.103375.(inpress).

[10] Kovács A (2015) Integrated Task Sequencing and Path Planning for Robotic Remote Laser Welding. *International Journal of Production Research*. http:// dx.doi.org/10.1080/00207543.2015.1057626. (in press).

[11] Reinhart G, Munzert U, Vogl W (2008) A Programming System for Robot-Based Remote-Laser-Welding with Conventional Optics. *CIRP Annals* 57(1):37–40.

[12] Franciosa P, Ceglarek D (2015) Hierarchical Synthesis of Multi-level Design Parameters in Assembly System. *CIRP Annals* 64(1).

[13] Ceglarek D, Huang W (2007) Mode-Based Decomposition of Part Form Error by Discrete-Cosine Transform with Implementation to Assembly and Stamping System with Compliant Parts. *CIRP Annals* 51(1):21–26.

[14] Huang W, et al (2014) Statistical Modal Analysis for Variation Characterization & Application in Manufacturing Quality Control. *IIE Transactions* 46(5): 497–511.

[15] Das A, Franciosa P, Yilmazer S, Ceglarek D (2015) Geometric Modal Analysis (GMA) for Shape Error Modeling and Analysis with Applications in Manufacturing. *IEEE Transactions on Industrial Informatics*.

[16] Franciosa P, Das A, Ceglarek D, et al (2014) Design Synthesis Methodology for Dimensional Management of Assembly Process with Compliant Non-ideal Parts. *Proceedings of Joint Conference on Mechanical, Design Engineering & Advanced Manufacturing*.

[17] Sinha AK, Kim DY, Ceglarek D (2013) Correlation Analysis of the Variation of Weld Seam and Tensile Strength in Laser Welding of Galvanized Steel. *Optics and Lasers in Engineering* 51:1143–1152.

[18] Prakash PKS, Franciosa P, Ceglarek D (2015) In-line Quality Monitoring and Performance Evaluation in Remote Laser Welding Applications. *IEEE Transac-tions on Industrial Informatics*.

[19] CONSAD (1998) Estimating Economic Impacts of New Dimensional Control Technology Applied to Automobile Body Manufacturing. *Journal of Technology Transfer* 23(2):53–60.

[20] Ceglarek D, Shi J, Wu SM (1994) A Knowledge-Based Diagnosis Approach for the Launch of the Auto-Body Assembly Process. *ASME Transactions Journal of Engineering for Industry* 116(4):491–499.

[21] Huang W, Phoomboplab T, Ceglarek D (2009) Process Capability Surrogate Model-Based Tolerance Synthesis for Multistage Manufacturing Systems. *IIE Transactions* 41:309–322.

[22] Al-ZaherA,ElMaraghyW(2013)DesignofReconfigurableAutomotiveFram-ing System.*CIRPAnnals*62(1):491–494.

[23] Chen Y, et al (2006) Integration of Tolerance and Maintenance Design for Multi-station Manufacturing Processes. *IEEE Transactions on Automation Sci-ence and Engineering* 3(4):440–453.

[24] Huang W, Ceglarek D (2004) Tolerance Analysis for Design of Multistage Manufacturing Processes Using Number-Theoretical Net Method (NT-net). *International Journal of Flexible Manufacturing Systems* 16(1):65–90.

[25] KongZ,CeglarekD(2003)RapidDeploymentofReconfigurableAssembly Fixtures UsingWorkspaceSynthesis&VisibilityAnalysis.*CIRPAnnals* 52(1):13–16.