iQonic

iQonic

Innovative strategies, sensing and process chains for increased Quality, re-configurability, and recyclability of Manufacturing Optoelectronics

Deliverable

D2.2 SoA analysis of assembly processes in respect to demonstrators

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DISCLAIMER

ABSTRACT

The following report is generated within the iQonic project, which concentrates on the development of micro-optic assemblies. The project target is to create a scalable zero-defect platform that employs flexible and sustainable assembly practices and technologies for micro-optics. The iQonic platform will be implemented using a holistic approach with eight strategies (DIAGNOSE, ADJUST, PREDICT, DETECT, PREVENT, MANAGE, SUSTAIN, REDESIGN), involving several different technologies from different branches of engineering and science. These technologies are described and benchmarked in this report with respect to the application fields of the project. The iQonic consortium will test the developed platform with four uses cases before the end of the project. These use cases are briefly described and linked to the iQonic technologies in this report. The mapping shows how each technology will be demonstrated and how the possible improvements to the state-of-the-art (SoA) can be seen in the end of the project. Moreover, the report considers the SoA of commonly known and widely accepted micro-optic assembly processes and in situ measurements used in the assembly processes.

The SoA analysis of the report points out that the project incorporates technologies, which are not used in the quality control of either manufacturing industry or micro-optics. iQonic also contains many technologies that have been used in somewhere else in the manufacturing industry, but are rare or have not been applied to photonic assemblies. In addition, the report shows that iQonic consortium will introduce new advanced features to technologies that already exist in the field. Due to the advances of the SoA by each iQonic technology in the field of micro-optics, the consortium will deliver a unique solution in the field of micro-optics where no similar multidisciplinary solution exists.

Scope

The report will focus on the SoA analysis of the iQonic technologies in the area of zero-defect manufacturing and micro-optics. This report also introduces the use cases that will be used to demonstrate iQonic technologies during the project. Furthermore, the present SoA of micro-optic assembly processes and measurements made during the assembly processes are considered.

ABBREVIATIONS

Accelerated lifetime testing	ALT
Artificial intelligence	AI
Augmented reality	AR
Catastrophic optical damage	CoD
Chip on carrier	COC
Coefficient of thermal expansion	CTE
Central processing unit	CPU
Cyber-Physical-Systems	CPS
Data acquisition	DaQ
Decision Support System	DSS
Degrees of freedom	DOF
Digital adaptive optics	DAO
Electronic product code	EPC
Enterprise Resource Planning	ERP
European Union	EU
Fiber Laser Modules	FLM
Human-machine interface	HMI
Internet of Things	IoT
Key performance factors	KPF
Key performance indicators	KPI
Knowledge based system	KBS
Light-current-voltage	LIV
Manufacturing execution system	MES
Metalorganic vapour phase epitaxy	MOCVD
Near infra-red	NIR
Original equipment manufacturer	OEM
Part level	PL
Point of sale	POS
Quantum Cascade Laser	QCL
Radio frequency identification	RFID
Red-Green-Blue	RGB
Random access memory	RAM
Resource description framework	RDF
Reverse Supply Chain	RSC
Robot operating system	ROS
Small and medium sized enterprise	SME
Software	SW
State-of-the-Art	SoA
Ultraviolet	UV
Independent software vendor	ISV
Vertical Surface Emitting laser	VCSEL
Virtual reality	VR
Visible	VIS
Work package	WP
Zero-Defect Manufacturing	ZDM

1 Introduction

The rapid increase in the demand of optoelectronic applications and devices has led the manufacturing industry towards new challenges in the development of equipment, instrumentation and fabrication processes due to the need of customization, lower fabrication costs, larger volumes, and increasing level of system and device complexity. In order to solve these new challenges, the manufacturing industry of optoelectronic systems and components is turning to (semi-)automated fabrication processes since the automation can increase yield and throughput, improve quality and reduce costs. However, there are various optoelectronic applications, in which a high level of customization is required for low or moderate volume of parts and systems. To cope with this requirement, the fabrication processes and systems must be flexible, quickly and easily re-tasked.

The iQonic consortium aims to develop a flexible, sustainable and scalable zero-defect production platform for systems with optoelectronics components. The developed platform will consider the optimization and design of the entire process chain and the assembly process. Moreover, the platform will incorporate the identification of possible defective (sub-) systems in the process chain, the possible rework, and the recycling of components back to the value chain at their end-of-life. The actors and stakeholders of iQonic project are presented in Table 1-1 and the consortium consists of industrial, academic associates, and SME companies.

Table 1-1: The iQonic project consortium

Short name	Name	Country
FRAUNHOFER*	*FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.*	Germany
ATLANTIS	*ATLANTIS ENGINEERING AE*	Greece
BRUNEL	*BRUNEL UNIVERSITY LONDON*	United Kingdom
CORE	*CORE INNOVATION AND TECHNOLOGY OE*	Greece
POLIMI	*POLITECNICO DI MILANO*	Italy
SHADOW	*THE SHADOW ROBOT COMPANY LIMITED*	United Kingdom
HOLONIX	*HOLONIX SRL-SPIN OFF DEL POLITECNICO DI MILANO*	Italy
SENSAP	*SENSAP SWISS AG*	Switzerland
IP-ASCR (HiLASE)	*FYZIKALNI USTAV AV CR V.V.I*	Czech Republic
PRIMA	*PRIMA ELECTRO SPA*	Italy
ALPES	*ALPES LASERS SA*	Switzerland
FORTH	*FOUNDATION FOR RESEARCH AND TECHNOLOGY HELLAS*	Greece
FILAR	*FILAR-OPTOMATERIALS SRL*	Italy
SACMI	*SACMI COOPERATIVA MECCANICI IMOLA SOCIETA COOPERATIVA*	Italy
FICONTEC	*FICONTEC SERVICE GMBH*	Germany
TAU	*TAMPERE UNIVERSITY*	Finland
BRIGHTERWAVE	*BRIGHTERWAVE OY*	Finland

*: Coordinator

To reach the project objectives, the iQonic consortium utilizes eight strategies (DIAGNOSE, PREDICT, ADJUST, PREVENT, DETECT, MANAGE, SUSTAIN, REDSIGN) supported by various hardware and software systems and technologies. The validity of the developed platform in the project will be tested in typical optoelectronic production environments using four use cases including laser diode manufacturing, crystal production, industrial laser systems, and miniaturized RGB lasers employed in augmented reality applications.

This report will concentrate on the positioning the project developments with respect to the advances in the field. It will link the project development to the demonstrators and describe how the project developments are reflected in the demonstrators. Particularly, the report will benchmark

- the present status of available in-situ measurements in micro-optical assembly processes, and
- the present assembly processes for optoelectronics manufacturing compared to the aimed project developments, pointing out also development scenarios for advanced functionalities of different component categories in Section 2.

In Section 3 the present status of developed technologies will be presented. This discussion includes analysis of how and why iQonic consortium can improve each of these technologies. Section 4 presents the brief introduction of use cases that demonstrate the capabilities of the project framework and links the developments in the project to demonstrators. Finally, Section 5 outlines the developments compared to the present and past research and technologies in the field.

2 Review of micro-optic assembly processes and insitu measurements

Various optical and micro-optic assembly systems have been developed over the years including[1 2 3 4 5 6]. Many of the recent initiatives are targeting fully-automated micro-optics assembly processes in order to reduce the cost per assembly and increasing yield and throughput. On the other hand, a high-degree of automation is known to decrease the level of flexibility and therefore various investigations have been conducted to make automated assembly processes easily re-configurable. Standardization and modularization have been demonstrated to be the most promising candidates to improve flexibility cost efficiently and still maintaining a high-level of automation in an assembly process[7 8]. In addition, the SCALAB project targeted for increasing the utilization time of automated assembly systems in the case of many different product variants[9].

There are various trade-offs between different process performance indicators in micro-optic assemblies. For instance, a high throughput can be more easily achieved with low placement accuracy, while a high placement accuracy requirement increases costs and decreases the throughput[10]. Similarly, the assembly process yield depend on the used assembly station, materials, geometries, required specifications and component tolerances, throughput and many other variables. Therefore, it is also difficult to compare yields of even very similar SoA assembly processes. For example, in a typical SoA assembly process just a relatively small change in the accuracy specifications can lead to a dramatic change in the process yield from 1% to 99%[11]. Moreover, micro-optic assembly processes have high sensitivity to perturbations, making the zero-defect manufacturing of these assemblies challenging. To improve the lifetime, quality control and performance of (micro-) manufacturing process chains several development projects have considered these topics:

- Minimizing Defects in Micro-Manufacturing applications (MIDEMMA)[12] FP7-NMP project targeted for adaptive quality control of micro-manufacturing. The project demonstrated that real-time process monitoring enable to use less expensive machines due to smaller variances in the fabrication process requiring ultra-high precision. The project also indicated that smart-decision making decreases the knowledge requirement of operators.

[1] Brecher, C., Pyschny, N., Haag, S., & Mueller, T. (2013, February). Automated assembly of VECSEL components. In Vertical External Cavity Surface Emitting Lasers (VECSELs) III (Vol. 8606, p. 86060I). International Society for Optics and Photonics

[2] Apacos project final report, available at https://cordis.europa.eu/project/rcn/106100/reporting/en, 31/1/2019

[3] Barwicz, Tymon, et al. "Automated, self-aligned assembly of 12 fibers per nanophotonic chip with standard microelectronics assembly tooling." Electronic Components and Technology Conference (ECTC), 2015 IEEE 65th. IEEE, 2015.

[4] Axt, Christoph, et al. DeLas (Development and ramp-up of automated laser assembly) project final report 2016.

[5] Cosmicc (H2020-ICT-27-2015- 688516)

[6] Photonic Integrated Circuits Assembly and Packaging Pilot Line, available at https://cordis.europa.eu/project/rcn/206352/factsheet/en, 7/2/2019

[7] Brecher, Christian, et al. "Integrative production technology for high-wage countries." Integrative production technology for high-wage countries. Springer, Berlin, Heidelberg, 2012. 17-76.

[8] Barwicz, Tymon, et al. "Automated, self-aligned assembly of 12 fibers per nanophotonic chip with standard microelectronics assembly tooling." Electronic Components and Technology Conference (ECTC), 2015 IEEE 65th. IEEE, 2015.

[9] Garlich, T., Guerrero, V., Hoppen, M., Müller, T., Pont, P., & Pyschny, N. (2012). SCALAB. Scalable Automation for Emerging Lab Production. Final report of the MNT-ERA. net research project, 1.

[10] Barwicz, Tymon, et al. "Automated, high-throughput photonic packaging." Optical Fiber Technology (2018).

[11] Heilala, J., et al. "LTCC technology for cost-effective packaging of photonic modules." Assembly Automation 25.1 (2005): 30-37.

[12] Minimizing Defects in Micro-Manufacturing Applications final project summary, available at https://cordis.europa.eu/project/rcn/101453/reporting/en, 8/2/2019

- MICROMANufacturing[13] is ongoing project aiming for research training. It provides innovative technological solutions, inter-disciplinary training in different domains of micro-manufacturing, and validation support for manufacturing processes.
- Zero-defect manufacturing strategies towards on-line production management for factories (Z-Fact0r)[14] is an ongoing project targeting for developing an integral solution for the manufacturing industry with a five stage strategy a) early detection of defects DETECT, b) the prediction of defect generation PREDICT, c) the prevention of defect generation by production line recalibration PREVENT, d) the reworking or remanufacturing of the product REPAIR, and e) the management of the a-d strategies by event modelling and real-time decision support MANAGE).
- Factory Automation Edge Computing Operating System Reference Implementation (FAR-EDGE) [15] is a project that combines leading experts in manufacturing, industrial automation, and future internet technologies to develop novel factory automation solutions based on future internet technologies.
- Z-Brea4k[16] project develops a novel predictive maintenance platform to eliminate unexpected breakdowns and extend the life of production systems.
- ForZDM[17] project concentrates on defect management strategies exploiting a distributed networks of heterogeneous multi-sensor data gathering services for high-value and low volume manufacturing processes.

Even though SoA assembly processes differ from each other as the complexity of assemblies increases, some assembly steps (please see Figure 2-1 below) are present almost in all micro-optic assembly processes. These steps are:

- Part feeding
- Component manipulation, handling
- Positioning and alignment
- Bonding
- Testing and in-situ measurements

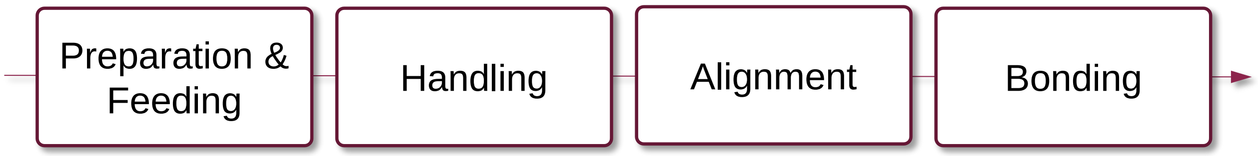

Figure 2-1: The classical process chain for the assembly of optical and photonic systems.

The present status of SoA in these process steps is described in the following subsections.

2.1 Part feeding

In micro-optics, optical surfaces must be kept perfectly clean in order to avoid defects and contamination, but the part feeding must also enable to pick up components with a rapid rate. Consequently, specially designed trays have been used to ensure that the components are stored in a safe contamination-free magazine[18].

Moreover, micromanipulators may have very limited travel ranges and therefore a feeder system such as a robot or a conveyor must be used in some cases to handover components from the magazine to the micromanipulator. The feeder system can have relatively low accuracy compared to the micromanipulator

[13] MICROMANunfacturing, the project webpage available at http://www.microman.mek.dtu.dk/, 8/2/2019
[14] The project web page is available at https://www.z-bre4k.eu/, 20/2/2019
[15] Factory Automation Edge Computing Operating System Reference Implementation, webpage available at http://www.faredge.eu/#/, 11/2/2019
[16] The project web page is available at https://www.z-bre4k.eu/, 20/2/2019
[17] The project web page is available at https://www.forzdmproject.eu/, 20/2/2019
[18] Zontar, Daniel, Sebastian Haag, and Christian Brecher. "Camera-guided Feeding of Optics in Robot-based Laser Assembly."

that is employed for placing components in an assembly. Alternatively, the system can contain a pick and place robot that picks up a component from the magazine and places it in the desired position. Industrial pick and place robots are particularly tempting because these systems have a short cycle time and enable high throughput. On the other hand, the tight placing accuracy requirements of micro-optics may be difficult to fulfill with industrial pick and place robots[19].

2.2 Component manipulation

Micromanipulators with different types of gripping tools are used to carry out highly controlled mechanical movements and target object manipulation. Today's industrial SoA micromanipulators can have 4 or 6-axis with a resolution in the range of a few tens of nanometers and repeatability below 500 nm[20]. The accuracy of SoA micromanipulators employing piezoelectric and electric actuators combined with position feedback sensors and motion control systems is so high that the post-bond positioning accuracy is usually limited by other factors and process variables.

The optimum gripping tool and strategy depend on many variables such as the shape, dimensions, materials and the required precision in component positioning. Furthermore, in micro-optics the component size can be orders of magnitude smaller than the handling tools, cameras and lenses. Consequently, the component may be obstructed, making the full 6-degrees-of-freedom (DOF) manipulation of a component cumbersome. In the micro-scale also surface forces such as electrostatics, van der Waals and surface tension can cause sticking effects in component handling degrading positioning accuracy since these forces become much more significant compared gravity than in macro-scale object handling.

Several different type of gripping tools have been employed in micro-optics. Mechanical micro-grippers have been developed for handling a broad range of components from 10 µm to several millimeters. Mechanical grippers utilize fast high-resolution precisely controlled short stroke piezoelectric element[21] or fast low cost pneumatic actuators. Vacuum tools typically operate with components larger than 100 microns while needle tips are used for components from 100 µm down to 1 µm[21]. Vacuum tools are relatively cheap and simple to replace since this type of grippers have a thin tube connected to a vacuum pump. Vacuum grippers enable to grab and place sensitive items that can break easily. Needle tips enable to operate with the smallest components, but this type of grippers can be sensitive to perturbations or suffer from reliability issues[21].

2.3 Positioning and alignment

In the positioning and bonding stage, a micro-optical component is picked up with a micromanipulator equipped with a gripping tool. Subsequently the component is pre-positioned to its nominal position prior to fine aligning the component in the assembly using active or passive alignment techniques.

If an active alignment process is available, it is usually the most accurate method to align a component in micro-optics. A typical active alignment process is carried out by monitoring one or multiple performance indicators simultaneously and employing this information as a feedback for closed loop control. In existing SoA 6-DOF systems alignment accuracy is usually high compared to post-bond accuracy (SoA post-bond misalignment is in a sub-µm range) that is also dependent on other process steps such as the bonding stage, grippers, adhesive shrinkage, component geometry and dimensions, component tolerances, and thermo-mechanical stress[22] [23]. Active alignment processes can directly verify that the subassembly fulfills the designed specifications due to the closed loop control, which leads to a high yield. Moreover, active alignment allows

[19] Sun, Yu, et al., eds. Micro-and nanomanipulation tools. Vol. 13. John Wiley & Sons, 2015.
[20] Piacentini, I., and T. Vahrenkamp. "Requirements for process automation of optical interconnect technologies." Optical Interconnects for Data Centers. 2017. 343-372.
[21] Clévy, Cédric, Arnaud Hubert, and Nicolas Chaillet. "Flexible micro-assembly system equipped with an automated tool changer." Journal of micro-nano mechatronics 4.1-2 (2008): 59.
[22] Mohaupt, M., Beckert, E., Eberhardt, R., & Tünnermann, A. (2010, February). Alignment procedures for micro-optics. In International Precision Assembly Seminar (pp. 143-150). Springer, Berlin, Heidelberg.
[23] Müller, Tobias, et al. "Robust adhesive precision bonding in automated assembly cells." International Precision Assembly Seminar. Springer, Berlin, Heidelberg, 2014.

larger component tolerances and fabrication inaccuracies. The main drawback of this method is low throughput.

There are several passive alignment techniques available such as vision-assisted, mechanical, and surface-tension-driven passive alignment methods, which also work for alignment when active alignment is not accessible. In a vision-assisted alignment process, machine vision is employed to identify the key features of a component prior to moving the component to the correct position. The accuracy of this method is usually limited by diffraction and calibrations. Due to these limitations, vision-assisted alignment processes are not as accurate as active alignment processes. Vision-assisted alignment has been also used as a coarse alignment before an active alignment process[24]. Mechanical alignment techniques utilize mechanical stoppers and jigs. Mechanical passive alignment processes have reached 1-2 µm alignment accuracy[25], but these techniques require precision-machined components, which can be expensive. Surface-tension-driven alignment is an accurate technique, which can reach extremely high throughput, good yield, and sub-µm accuracy with low costs even for very small components[26] [27]. However, the assembly process design that takes into account fabrication inaccuracies can be challenging to carry out[26].

2.4 Bonding

Due to the small component dimensions in micro-optics, it is not usually possible to use mechanical clamping to fasten components in place. SoA micro-optic assembly processes usually employ UV-epoxy bonding, laser welding, and soldering to fix components in position.

Component bonding with UV-curable epoxy is a flexible low-cost method that can withstand relatively large component fabrication tolerances and numerous UV-curable epoxies are available for component bonding with different properties (i.e. viscosity, curing time, etc.). On the other hand, UV-epoxies have inherently volumetric shrinkage (2-5%), which degrades the post-pond alignment accuracy of bonded micro-optic UV-transparent components. The effect of shrinkage is minimized by pre-compensation, component design, and making the glue-gap as small as possible taking into account the tolerance-chain of bonded components. The throughput is relatively low and the process step time varies from tens of seconds to minutes.

Laser welding provides a good production rate, high yield, and excellent mechanical reliability. Laser welding also avoids outgassing that is also one of the main issues with epoxies. The main disadvantages of laser welding are thermally induced component misplacement and the need of expensive high-resolution machine vision assisted welding spot positioning.

Laser soldering is particularly used for large multicomponent assemblies. In laser soldering after the coarse alignment, the solder is melted using a laser that heats up the solder locally. Both laser welding and soldering can maintain high thermal conductivity over the joint. Due to the coefficient of thermal expansion (CTE) mismatch and low melting point, laser soldering has poorer reliability over thermal cycles and at elevated temperatures compared to laser welding.

2.5 Testing and in-situ measurements

Today’s SoA micro-optic assemblies can have a huge amount of different characteristics defining the performance of the assembly. Due to measurement complexity and the high costs of the instrumentation, many of those characteristics are measured before or after the assembly process is completed. To minimize costs and increase throughput relatively simple measurements such as automated vision inspection, light-voltage-current (LIV), beam profiling are typically carried out during the assembly process. Accurate distance, position and

[24] Piacentini, I., and T. Vahrenkamp. "Requirements for process automation of optical interconnect technologies." Optical Interconnects for Data Centers. 2017. 343-372.
[25] Barwicz, Tymon, et al. "Automated, high-throughput photonic packaging." Optical Fiber Technology (2018).
[26] Mastrangeli, Massimo, et al. "Surface tension-driven self-alignment." Soft Matter 13.2 (2017): 304-327.
[27] Park, Hwan-Pil, et al. "Effects of Solder Volume and Reflow Conditions on Self-Alignment Accuracy for Fan-Out Package Applications." Journal of Electronic Materials 47.1 (2018): 133-141.

orientation measurement systems such laser interferometers have been incorporated with the assembly stations[19].

Due to positioning accuracy limitations and the manufacturing tolerance of components and assembly tools, the assembly processes allowing only very small tolerances are usually sensor guided. The instantaneous feedback from sensors enables to compensate deviations and environmental conditions that affect the process performance. The feedback can be provided by vision systems[28], positioning systems[29], or force gauges[30] [31]. Force sensors can be also used to prevent sensitive components from breaking down.

[28] Tamadazte, B., Piat, N. L. F., & Dembélé, S. (2011). Robotic micromanipulation and microassembly using monoview and multiscale visual servoing. IEEE/ASME Transactions on Mechatronics, 16(2), 277-287.

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[30] Shen, Y., Xi, N., & Li, W. J. (2003, October). Force-guided assembly of micro mirrors. In Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on (Vol. 3, pp. 2149-2154). IEEE.

[31] Komati, B., Rabenorosoa, K., Clévy, C., & Lutz, P. (2013). Automated guiding task of a flexible micropart using a two-sensing-finger microgripper. IEEE Transactions on Automation Science and Engineering, 10(3), 515-524.

3 The SoA of the project developments

The iQonic consortium will consider and develop various technologies in the project that will be integrated into the final solution that will be implemented into optoelectronic manufacturing pilot scenarios. In this section for each of these technologies a brief description, the current development status and the reasons why and how the consortium can advance in the state-of-the-art are presented.

3.1 Assembly process design, analysis and optimization (F-IOF)

The classical process chain for the assembly of optical components, as depicted in Figure 2-1 (Section 2), can be seen as a sequential line of processes that usually don't make use of historical or inline data generation throughout this chain. In photonics assembly there are of course already various data sources implemented. Those are extensive component characterization techniques during preparation and feeding, in particular by means of taking camera or microscopy based images from optical surfaces (e.g. lens surfaces or laser facets) and judging them regarding present contaminations and defects such as cracks. Data generated during such characterizations are mainly used for a fail/pass decision for further usage of the component, and rarely are used for an adaption of the sub-sequent processes regarding specific detected properties of the component in question. During handling only basic data such as presence of the component inside the handling tool is generated, which also leads to a fail/pass decision for the handling sub-process. Alignment as one of the two most crucial and critical process in assembly tries to optimize the alignment result by pure knowledge about the optimal alignment position and potential systematic errors during alignment and sub-sequent bonding, for which pre-compensation techniques are then applied. Bonding itself aims for lowest de-alignment during bonding and for sufficient strength, but does not take other effects such as bonding contamination and stochastic de-alignment into account. In principle, each assembly process thus each process is optimized on its own by process development and parameter variation, once a process is established there rarely is an update of the process model with respect to the developing historical and inline data.

The advance of iQonic thus can take place by the more complete gathering of data regarding the component's state during all processes of photonic assembly. The goal would be to optimize the overall outcome of the process chain regarding alignment and stability of the component's functionality over the whole lifetime (zero defect). Particular goal would be to optimize for changing systematic errors during handling, alignment and bonding, and taking knowledge from preparation and feeding into account. Optimization figure of merit would be the alignment state and a (pre-) compensation for effects such as:

- Component deformation during handling,
- Machine drifts during time-expensive alignment processes,
- De-alignment during bonding, e.g. due to adhesive shrinkage during curing,
- Functionality degradation due to process effects such as outgassing,
- De-alignment due to known environmental effects during lifetime of the system (fed back into the process control by updated historical data).

Structured data gathering, its judgement and thereon based process modelling and control updates of the assembly process as well as decision support for gates in the process chain are the envisaged iQonic advances over the SoA, as parts of such approaches are established in very specialized fields of optics and photonics (e.g. high value lithography systems), but are not widely adopted at all in the general photonics industry. Not only establishing data and intelligence driven processes, but also disseminating them into the photonics assembly world via standards and stakeholder adoptions are of importance for a wide acceptance of the technologies developed in iQonic.

3.2 Decision support system (ATLANTIS)

Decision support system (DSS) is a system in a developing state that needs to be improved regularly to reach in state of business readiness. As a part of the iQonic project, DSS needs to improve the algorithms for the rule engine. The rule engine is now based on finite state machines[32 33], which define the rule in a deterministic way, although decision support process is a non – deterministic one. Non – deterministic state machine and artificial neural networks[32 34] are some of the algorithms that can be used by the DSS in the iQonic project in parallel with the finite state machines. The DSS feedback loop for consuming its own data is one of the next steps of DSS development. This step requires the definition of the DSS database schema, the definition of the format of the outcoming DSS data and its implementation. Furthermore, the communication API that is now in use should be enhanced creating a tool which will be independent and could be used for various purposes and cover most of the available sensorial data.

Most of the KPIs for the DSS will be defined during the course of the project, and will depend on the rest of the IQONIC's system architecture. At this stage of the project, the KPIs that can be defined beforehand are:

1. size of the database (needed),
2. time span of the database (how long should data be available),
3. availability of suitable communications protocols,
4. internet connection speed (needed for the DSS installation and the notification),
5. resources on the server side for the installation,
6. maximum users (the number of the users DSS can serve)[34],maximum rules (that can run concurrently)[34].

iQonic can advance the DSS SoA because it is the first project that its main focus is outside the shop maintenance scope. The rule engine should be trained with different purpose and for data coming from new sensors. Both the purpose and the data address new challenges for the DSS. On the other hand, the iQonic consortium is supported by European Union, which guarantees the quality of the developed systems. In that context, DSS will be improved in an environment which has not yet been test, but with the security provided by European research projects. The iQonic consortium gives the flexibility to address known issues in the DSS development outside its regular purpose of use.

Some of the main restriction for DSS concerning the iQonic project are related with the availability of: suitable sensors, data from industrial users, suitable people to work on the project, communication protocols while being associated with the restricted data communication due to lack of sensors and due to the security reasons on the shop floors[34 35].

3.3 Reverse supply chain (ATLANTIS)

Reverse supply chain (RSC) is a special data and knowledge driven DSS that refers to actions to be taken, when a defected part, during the production process is discovered. The software system can consume data from web services and RabbitMQ queues also. Its philosophy is that in a scheduled timely manner, it syncs required data from the various data sources that is necessary for the user to build the rule later. After the operator has created a set of rules then the defects information is consumed and based on the executed rule, the suggests a specific action. A rule-based engine will be used, with rules defining the conditions to be met (e.g. defect severity and type, recoverable, value to recover, reparable, defect origin, stage). Any executed can provide, rule at the moment, one of the following suggested actions "repair and add it back to the production line", "return to supplier", "recycle", "dispose".

Zero-Defect Manufacturing Reverse Supply Chain (ZDM RSC) is a state-of-the-art software application of ATLANTIS. The Reverse Supply Chain (RSC) process of iQonic will be designed and further developed, and most of the KPIs will be defined during the project's progress, and depends on the rest of the IQONIC's system architecture. At this current stage of the project, the possible initial KPIs that can be defined are:

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[32] https://www.tutorialspoint.com/, 6/3/2019
[33] Anderson, J. A., 2006. Automata Theory with Modern Applications. 1st ed. Cambirdge: Cambridge Univesity Press.
[34] Haykin, S., 2009. Neural Networks and Learning Machines. 3rd ed. Hamilton, Ontario: Pearson - Prentice Hall. COMPOSITION – D3.9 – Manufacturing Decision Support System II
[35] SatisFactory – D3.5 - Shopfloor Feedback Engine and DSS

1. execution speed of business scenarios,
2. incoming data rate per minute,
3. ensure low ceremony for low RAM and CPU consumption,
4. application availability – be constantly online.

iQonic can advance the RSC SoA as during the production process, with the support of the RSC assembly, the operators and the technical managers will have a more substantive control over the products/materials. This will lead to a holistic monitoring of the whole process chain, allowing more accurate decisions on their characterisation and testing approaches. This new process will aim for more than 20% introduction of recycled and recovered parts in the production to reduce the material costs by 12%.

Some of the main restriction for RSC concerning the iQonic project are related with the availability of data from end users (including bad format, irrelevant values in data messages or corrupted data) and not compatible software or/and hardware for RSC installation.

3.4 Higher Level Communication Middleware (ATLANTIS)

Middleware is the application for interfacing with Manufacturing Execution Systems (MES) and other higher-level management systems in order to exchange data, alarms about predicted/detected defects, recommendations, production and product requirements. To this end there will be exploration of standardised protocols and communication means (OPC, OPC-UA, UMCM), based on industrial standards (e.g. IEC 62714, IEC 62264, OPC UA). Furthermore, the middleware shall perform the semantic modelling of the data to be exchanged for interfacing with MES and other higher-level management systems. This calls for semantic annotation of all exchanged data and use of appropriate ontology elements.

More specific key performance indicators for the Middleware will be defined during the course of the project. Some key performance indicators (KPIs) that middleware should present for desirable performance are the following[36] [37]:

1. interoperability,
2. reliability,
3. availability,
4. responsiveness,
5. processing delay - processing performance,
6. quality (customer satisfaction),
7. overall efficiency,
8. scalability,
9. reduced cost,
10. optimization of the production process.

iQonic consortium can advance SoA since the project will be built with architecture interoperability from the outset, using the concept of IoT Middleware for interfacing with any metrology/inspection and other tools. Additionally, while the iQonic consortium is supported by European Union, which guarantees the quality of the developed systems, it is a retrofitting solution also based on the current infrastructure that minimises the needs of high investments.

Some of the main restriction when talking of Middleware, are related with no widely accepted standards in the market for the communication among shop-floor h/w and s/w assets and metrology sensors and inspection systems, especially with respect to the data being exchanged and processed (emphasised at EFFRA conference, September-2016), no support of semantic modelling and managing of data volumes[36], problem of scalability of the communication and object management algorithms.

[36] S. Bandyopadhyay, M. Sengupta, S. Maiti, S. Dutta, ROLE OF MIDDLEWARE FOR INTERNET OF THINGS: A STUDY International Journal of Computer Science and Engineering Survey (IJCSES), vol. 2, no. 3, August 2011.
[37] Farahzadi, Shams, Rezazadeh, and Farahbakhsh. “Middleware technologies for cloud of things: a survey”, April 2017.

3.5 Knowledge based system (HOLONIX)

In the framework of iQonic project, Holonix will develop a Knowledge Based System (KBS) to extract, store, and retrieve all the relevant information enriched with semantic annotations to guarantee a prompt identification of criticalities in the process. For this purpose, a special data storage is required, in order to deal with triplex collections. One of the common framework for implementation of triple store is the Resource Description Framework (RDF), which is a standard model for data interchange on the web. The RDF repository is in the form of Triplestore, which is designed to store and retrieve identities conducted from triplex collections representing a subject-predicate-object relationship. On top of the Database a reasoning engine will create relationships and allow to extract knowledge to be consumed by other components, or directly by the end users. Semantic Web Service components will support management of the RDF repository in the way of search, authentication, dataset, revision, and SPARQL.

The KBS will be integrated in a more general production-monitoring framework, designed to support different actors of the company to evaluate products and production systems conditions in order to increase productivity and avoid defects. Data will be acquired form sensors installed around the machines specialized in gathering the intrinsic and extrinsic production systems parameters, and correlated with product and production information.

Such an approach is not common practice in manufacturing, and in particular in opto-electronics production. Recent developments in IoT (Internet of Things) enabled the data gathering, storage, analysis and visualisation form various sources, including production systems, but the industrial application of the solutions developed is still in its infancy. In this context, a particular focus has been placed on zero-defect manufacturing, a concept that aims at minimise products defects and maximise the yield. This is made possible by the cross-correlation and analysis of production data, machines/production systems data and products quality control data. No complete solution is already available on the market, but dedicated innovation projects are being developed in various contexts including EU funded projects (e.g: H2020 Z-Fact0r, H2020 GO0DMAN,…). The most common approach is based on SW platforms using architecture based only on Relational Databases. On one hand this allows to have a good management of real-time data, on the other hand it is not optimal for knowledge extraction. Knowledge management corresponds to a wide set of methods and techniques which are utilised in order to represent, distribute and reuse information, know-how and other[38], pointing out one more need of manufacturing environment today. Also, it is noticed that a lot of companies do not know the exact knowledge that they pose within their databases. In this framework, the application of a KBS can bring multiple advantages, since it can ease the extraction of knowledge, improve interoperability and favour the satisfaction of user requirements, since knowledge representation acts as a bridge between end users of a SW platform and platform developers.

The proposed framework will support production managers during the daily production monitor and assessments and by workers to detect defects in order to act in short time. The technology here proposed can be applied to all the iQonic case studies.

3.6 Early detection and prediction engine (CORE/FIC)

iQonic will aim to develop advanced machine learning techniques and models involving:

- Trend analysis techniques for optoelectronics machines
- Ensemble models for increased accuracy
- Hyperparameter optimisation to fine-tune the ensembles
- Deep learning models working in parallel and synergistically to increase accuracy and predict future trends.

[38] Chryssolouris, G., Mourtzis, D., Papakostas, N., Papachatzakis, Z., & Xeromerites, S. (2008). Knowledge management paradigms in selected manufacturing case studies. In Methods and tools for effective knowledge life-Cycle-Management (pp. 521-532). Springer, Berlin, Heidelberg.

These techniques and models will be deployed on the production processes that will monitor and capture information from the process, environment and products. The functionality will be a decision in the form of detection of anomalies (states where the operation is not happening as it should). These anomalies, given further insights, will be developed as a classification model that categorises the type of trend / machine condition. Furthermore, predictions on future states of the machine will also be available, informing about potential malfunctions / less than ideal states. These will be interfaced with the data acquisition and database systems of iQonic and made available as outputs to the decision support system.

Specifically, for the in-situ measurements, the proposed methodology will enhance their significance, as they will not only be utilized after the process, but they will enable a smart process where the manufacturing depends on them. Moving from post-processing to a real-time utilisation scenario. The assembly processes, as well, will be able to move from a static setting based on batch, to a more dynamic operational mode, where the feedback control loop will inform and adjust according to the insitu measurements, to alter the process in such a way as to achieve zero-defects and minimum downtime.

So far only very simple algorithms are used to track possible malfunctions in optoelectronic assembly machines. For example, individual values are tracked and in case of abnormal behaviour a message is send to the operator. No interactions between different sensor data or a correlation of a combination of sensor data and the quality of the final product are tracked.

The expertise available within the iQonic consortium covers a whole matrix of disciplines required to enable development and advance the SoA. In fact, iQonic bridges the optoelectronics sector with the zero-defect manufacturing one. CORE, having strong background in Artificial intelligence and Machine learning in particular, focuses on giving insights from data and enabling intelligence on a machine level, while having significant prior expertise in other projects (Z-Bre4k, PVadapt, etc.). CORE's advancement of SoA relies on data acquisition from sensors, process knowledge and real testing environments, which are all addressed more than adequately by iQonic's consortium partners. In iQonic, CORE will research and develop new methods for trend analysis techniques that are able to identify structural changes in the profile of a time series.

3.7 Smart Tagging for automatic setting up the process chain parameters (SENSAP)

The "smart" tagging process consist of the data carriers (barcodes, RFID tags) and the appropriate hardware infrastructure (reader/writer, antennas and controller) with an optional endpoint (HMI) for the operator input. The overall process of the tagging scenario is to trace the product under production (and optional the used raw materials, EPC global[39]) throughout all the production chain of optoelectronics. At each production step (defined at WP2, WP3) the product will be registered and the initial configuration (recipe) parameters will be loaded to the production machine/phase. During the production phase the iQonic strategies will update (synchronize) the parameters based on their analytics results/decisions but also, the tag of the product will be updated with the information needed to proceed to the next production step (e.g. extrinsic parameters, product status). Moreover, if needed a special tag (active/passive [40] [41]) with embedded sensors (temperature, humidity) will be employed in critical components, which are affected by environmental factors during its transportation/storage.

In addition, using a handheld RFID reader the operator is able to easily identify the status of the product (e.g. faulty, repairable) and by an ad-hoc phase (e.g. visual inspection) altering in-situ the product characterization reintroduced it to the production process.

The key performance indexes for the smart tagging system will be defined during the project and specifically at WP3, based on the overall iQonic architecture. Nevertheless, the following KPI's can be defined at this stage

- Effectiveness: "do the right things" – setting up the production phase according to the product specifications.

[39] GS1, "Home: EPCglobal," GS1, [Online]. Available: https://www.gs1.org/epcglobal.
[40] R. Weinstein, " A Technical Overview and Its Application to the Enterprise," ITProfessional, vol. 7, no. 03, pp. 27-33, 2005.
[41] M. M. O. B. M. R. Michael ten Hompel, "Automatic Identification Technology," in Operations, Logistics and Supply Chain Management, Springer, 2018, pp. 687-718.

- Efficiency: “do things right” - set-up the correct parameters for the production phase.
- Yield: increased by the automate loading of the parameters (decrease set-up time).
- Performance: increase the overall production rate by the identification of product status from previous productions stages.
- Flexibility: the system allows the adaptation of the production chain according to the semi-produced product.
- Reliability: delivering the correct product at the correct place.

Moreover, the smart tagging allows for new metrics as

- Item Location,
- Length of time in a location ("dwell time", time-stamps for when the product was moved, shipped or received)

The iQonic consortium covers a wide area of different disciplines, required to advance SoA of the proposed (O4[42]) *smart tagging* development. In addition, the defined use-cases for the actual problem of the opto-electronics production chain provides the suitable ground for the development and test of such a solution. Although, the smart tagging scheme is based on barcodes/RFID tags which are employed by the retailers and warehouse management systems for asset tracking and POS (Point Of Sale), the iQonic consortium could introduce its use to the industrial production chain. A new implementation/development using this technology, similar to the automatic loading of the recipe[43] for a microwave (special designed by Barilla), can be successfully deployed as part of the iQonic project with the security provided by European research projects.

To summarize, smart tagging system will transform the product under production to a “smart” product communicate its status to the machines/phases and be easily traced. The needed functionalities besides the basics (registration and tracking) and the defined parameters of the product (product passport, WP3 and WP4) will be identified through the detailed design of the use cases (WP2).

3.8 Multi-sensorial network data acquisation/sensor distributed networks (SENSAP)

As it was described in our proposal[42], the manufacturing production chain of the opto-electronics is only affordable when performed in many stages and in multiple locations. This scatters the information related to the final produced product among different fabrications processes and machines.

A significant issue in the integration of machines/services from different machine builders/ISV is the establishment of the communication infrastructure among them. A communication architecture, the modelling of the data (semantics) and a common production procedure in fabrication is an essential development to the iQonic project.

The multi-sensorial network (fog computing[44]) will employ a central controller/edge device dedicated to each or multiple related production phases in-situ that will acquire and collects/process the production data based on the data models (WP2, WP3) from multiple sensors (digital, analog), quality inspection systems and other data sources. The edge devise will transfer collected (fusion, processed) data to the middleware (WP4, WP6) through the appropriate connectors and data shaping (data modeling, WP4). The described architecture aligned with the fundamental layers of the internet of things architectures current proposed by different researchers and groups[44]. In addition, it will provide an HMI panel to the operator visualizing the calculated KPI’s and relevant production order information.

The multi-sensorial acquisition network as the core infrastructure of the iQonic platform will have a major impact to the higher levels (strategies) of the iQonic platform. At this stage of the project, the following KPI’s are identified:

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[42] IQONIC, “IQONIC,” EU GRANT AGREEMENT NUMBER - 820677, 2018.
[43] J. Eagle, “Barilla to expand RFID-enabled recipes for automated home cooking,” 8 November 2018. [Online]. Available: https://www.bakeryandsnacks.com/Article/2017/11/08/Barilla-to-expand-RFID-enabled-recipes-for-automated-home-cooking?utm_source=copyright&utm_medium=OnSite&utm_campaign=copyright
[44] S. G. Tzafestas, “The Internet of Things: A Conceptual Guided Tour,” European Journal of Advances in Engineering and Technology, pp. 745-767, 2018.

- Performance: regarding the update rate and the size of the acquired data.
- Reliability: employing well defined communication protocols to assure the integrity of the data.
- Security: using standards for securing the data access and transmission.
- Response: the system response on events and alarms.
- Interoperability: support to a diversity of data sources and higher level systems (ERP/MES)
- Expandability: easily expand to incorporate new data sources/sensors

The key component of an industrial system is the sensor that feed the data to the controller and to the other operational systems that runs the plant[45]. A network of sensors is been in use for years, but in the era of industry 4.0 every sensor is now part of the overall architecture (IoT). This brought new challenges in the design and implementation of a sensorial network. In addition, the increasing computing power closer to the sensor reveal more capabilities and functions especially for the legacy systems. An overall description of an industrial IoT sensor would be a complex collection of hardware and software which bridge the gap between the device at the edge (shopfloor) to the services at the cloud (strategies)[46]. Based on the typical service life of an industrial equipment, which is measured in decades, we can state that there is a huge base of installed sensors that need to be modernized in order to be part of the industrial IoT network architecture.

As a typical industrial equipment has a service life measured in decades, there is a huge installed sensor base that needs conversion to internet connectivity.

The iQonic consortium can advance the SoA of the proposed development with its solid and diverse technological partners and the defined use-cases. The technological partners with their experience and their demand for data push the SoA of the proposed acquisition data network and with their diversity on the quality of the data (informative) provides the essential key performances indexes for the deployment of such a network. The overall consortium experience regarding data sharing among different machines builders, production processes enables and support the development of the overall architecture of an IoT system architecture[47].

3.9 3D-inspection methodologies (SENSAP)

The benefits of using a machine vision inspection system in a production line (e.g. accuracy, repeatability) are well established and it is noticeable that the European machine vision industry has more than double in the years 2008-2017[48]. This confirms the adaptation of the machine vision technology from the industry.

The iQonic will introduce a visual inspection module regarding the geometry characteristics of the component used in assembly process at Part Level (PL). It will be deployed at critical stages of the production chain as these will be defined at WP2 and WP3 regarding use cases.

The vision inspection quality system will provide at early stages of the production chain the metrics (data) that through iQonic strategies will lead to a zero-manufacturing process.

The visual inspection module will elaborate the product quality and supply the relevant results to the iQonic strategies for taking the appropriate actions regarding the product flow through the production chain. The KPI's of the vision system (lead to the system specifications) summarized bellow

- Performance: The rate of the evaluation of the inspected product unit.
- Accuracy: The accuracy of the inspected feature against a known specification indicating the true value of the quantity.
- Repeatability: variation from their mean.
- Flexibility: multiple inspection features.

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[45] Pallavi Sethi and Smruti R. Sarangi, "Internet of Things: Architectures, Protocols, and Applications," Journal of Electrical and Computer Engineering, vol. 2017, Article ID 9324035, 25 pages, 2017. https://doi.org/10.1155/2017/9324035.
[46] F.Zezulka, P.Marcon, I.Vesely, O.Sajdl "Industry 4.0 – An Introduction in the phenomenon", Elsevier, IFAC, Volume 49, Issue 25, 2016, Pages 8-12
[47] S. G. Tzafestas, "The Internet of Things: A Conceptual Guided Tour," European Journal of Advances in Engineering and Technology, pp. 745-767, 2018.
[48] VDMA, "Machine Vision 2018/19," VDMA Verlag GmbH, Frankfurt, 2018.

- Interoperability: communicate results aligned with the data modelling of the IQONIC platform.

In the field of 3D visual inspection methodologies, many solutions have been developed over the recent years, but the developed 3D solutions usually require a human operator or long setup time[49]. Moreover, these technologies are typically use case oriented. 3D visual inspection is mainly used in two application areas in the field of industrial manufacturing; 1) system guidance and 2) quality control. In both application areas manual and fully automatic configurations exist, enabling fast surface scans, automatic defect and feature recognition, and defect classification, for example[50]. SoA optoelectronic assembly stations typically employ one or multiple 2D visual inspection systems and 3D systems are rare. 3D inspection systems could provide several advantages over 2D systems including volume, surface flatness and roughness detection, and the recognition of features having negligible colour contrast with the environment. Moreover, the 2D visual inspection of an object requires accurate information about the distance between the object and the camera lens, unlike in 3D visual inspection methodologies.

The Inspection & metrology infrastructure can be advanced by the iQonic consortium based on the overall partners experience and speciality. The Inspection & metrology infrastructure needs to address the specifications and requirements depict in earlier work packages (WP2, WP3) assembled by the consortium. The consortium blend of OEM's, technological providers and end-users (use-cases) can advance the SoA by identifying the critical parameters to be captured and the places for the quality inspections the optoelectronic production chain needs to achieve the overall targets of the iQonic project.

3.10 Electronic nose (SACMI)

The electronic nose will be used to detect the presence of volatile organic compounds that are associated to the presence of chemical defects in the materials (e.g. crystals) used in the manufacturing of optoelectronic components.

The use of olfactory electronic sensors for in-situ measurements to monitor an industrial process represents a novel application area for electronic noses. The validation obtained on optoelectronics manufacturing could be taken as a reference to extend the applications of electronic noses to different industrial processes. Moreover, the interfacing of electronic noses with an external data acquisition platform linked to a decision support system perfectly fits within the framework of Industry 4.0 that SACMI is also developing on its ceramics and packaging plants.

The iQonic consortium can advance SoA by providing its knowledge on the interfacing of different measurement systems and on the development of a decision support system. The use-cases in the consortium represent a significant opportunity to validate the application of an electronic nose to monitor an industrial process and to assess the quality of optoelectronic materials and devices.

3.11 CPS for defects evaluation for reuse-requelification of products (POLIMI)

Defect management policies commonly adopted in manufacturing systems are scrapping and off-line reworking of defective items. The application of these expensive and low added-value alternatives is mainly due to the late identification of the defect in multi-stage systems, typically based on end-of-line inspection. At the state of the art, rework takes place mainly manually and off-line, i.e. at considerable cost and time. Indeed, when all the processes have been performed on the product, it is technically challenging and expensive to disassemble and repair or reuse components from defective products. As a consequence, scrapping and reworking result into significant economic losses because of the value of scrapped parts or the production time wasted for reworking, thus undermining the achievement of target due-date performance of the line, ultimately resulting in a loss of competitiveness for the manufacturer.

[49] Liu, Z., Ukida, H., Ramuhalli, P., & Niel, K. (2015). Integrated Imaging and Vision Techniques for Industrial Inspection. Springer.
[50] https://www.isravision.com/en/semiconductor/applications/wafer-production/surface-defects/surfqscan/" 9/3/2019

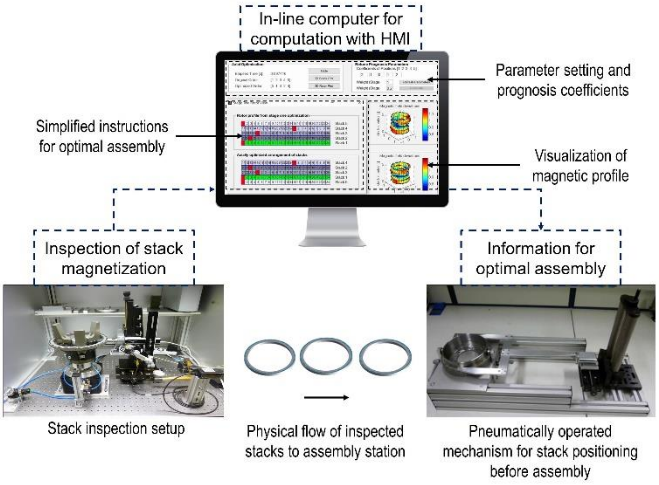

Figure 3-1: Example of CPS for in-line defect management demonstrated at Bosch in the EU project MuProd[51].

On the contrary, when in-line monitoring and inspection is adopted, especially for high-value parts, defects can be detected in line and requalification or reuse practices can potentially be activated with lower complexity and higher efficiency. Recent research has shown the feasibility of these innovative defect management strategies. For example, within the EU project MuProD, a new in-line repair strategy for restoring the quality of electric drive rotors during the assembly process-chain was demonstrated at Bosch 51 (Fig. 3-1). A new in-line inspection technology was developed to gather the magnetization profile of the rotor stacks and this information was elaborated by a physics-based model of the rotor with the objective to adjust the downstream stack assembly process based on the quality of the produced stacks. This solution was demonstrated to bring an improvement of system effective throughput of about 20% with a scrap rate below 0.1%. A similar approach was implemented in a manufacturing system producing batteries for electric vehicles[52]. These innovative approaches could bring huge gains in quality, productivity and sustainability performance mainly by reducing the generation of waste, reducing reworking efforts and increasing the robustness of the system in meeting its target due-dates. These new results have clearly indicated the advantage of proactive defect mitigation solutions against traditional reactive solutions. However, they require the development of specific in-line Cyber-Physical-Systems (CPSs) able to quickly elaborate sensor data by advanced algorithms to adjust the process and correct the defect or, if not possible, reuse valuable components through disassembly and regeneration operations. CPSs are usually defined as systems integrating computation and physical actuation capabilities 53, thus enabling model-based, feed-forward control of complex multi-stage process.

Although CPSs are seen as the core of the future industrial control systems under an industry 4.0 perspective, in industrial automation, more precisely in automation engineering, this concept is still not well developed. If properly designed and implemented, these systems can represent important technological enablers for sustainable manufacturing, making it possible to convert an otherwise wasted component into a regenerated and reusable product for manufacturing a new part or to be used as a spare part in the aftermarket business[54].

In spite of the recent developments, methods to systematically apply these strategies for reuse-requalify defective parts in complex manufacturing environments, such as the opto-electronics industry, are not available in the market. The main challenges in these applications relate to (1) the characterization of part variation modes and defect types ad degree in complex shaped micro-parts, (2) the high value of parts calling for small

[51] Colledani, M., Coupek, D., Verl, A., Aichele, J., Yemane, A., A cyber-physical system for quality-oriented assembly of automotive electric motors, CIRP Journal of Manufacturing Science and Technology, 20, Pages 12-22, 2018.
[52] Ju F, Li J, Xiao G, Huang N, Biller S, 2014, A Quality Flow Model in Battery Manufacturing Systems for Electric Vehicles. IEEE Transactions on Automation Science and Engineering 11(1):230–244.
[53] Lee, J., Bagheri, B., Kao, H.-A., 2015, A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems. Manufacturing Letters, 3:18–23.
[54] Colledani, M., Battaya, O., A Decision Support System to Manage the Quality of End-of-Life Products in Disassembly Systems, CIRP Annals - Manufacturing Technology, Volume 65, Issue 1, 2016.

inventory, (3) the gap in operator skills in adopting new CPS driven defect management strategies, (4) the high risk perceived by end-users in making this transition. Demonstrating that optimized defect management and reduction solutions based on CPS can significantly improve the quality and reusability of opto-electronic assemblies, components and materials will therefore contribute to open a totally new wave of high-tech applications, boosting the market of CPS-based solutions for zero defect manufacturing in the European industry.

iQonic will develop a new on-line solution for defect management in high-precision multi-stage systems for optoelectronics components based on the following building blocks and key rationales:

- The data gathered by the distributed inspection system will be integrated with physics-based models for developing a decision support CPS able to suggest the best defect management policy among (i) in-line repair by adjustment of downstream processes, (i) component dismantling for direct reuse, or (iii) component dismantling for reuse after regeneration.
- Based on this decision support system outcome, the selected defect compensation solution will be implemented in-line, adjusting the process parameters and procedure according to the outcome of the CPS.
- This new cyber-enabled manufacturing strategy will function as a feed-forward control solution for zero-defect manufacturing and critical materials waste reduction to be expensively implemented, tested and demonstrated on-line in the different iQonic use-cases.

3.12 Smart Grasping hand for increased precision/accuracy (SHADOW)

Shadow designs and manufactures state-of-the-art anthropomorphic robot hands and related systems. Shadow is one of Britain's longest-running robotics firms and the leading experts for technology around grasping and manipulation for robotics. For the project Shadow is proposing to use a hand attached to an arm in order to manipulate optoelectronic components or tools.

Figure 3-2: The left panel shows a picture from Shadow Dexterous Hand. The gripper will be enhanced for the use cases of iQonic project. The right panel present a picture from Modular Grasper.

The Shadow Dexterous Hand, shown in the left panel of Figure 3-2, is the most advanced commercial robotic hand available in the world, offering the full movement capability of the human hand. Customers include NASA, ESA, UK MOD, Hughes Research, and a range of top university research groups in Europe, USA, Japan and China. Shadow is applying their Dextrous Hand technology, looking at applications where human dexterity is required but the presence of humans is undesirable. The Dextrous Hand offers the possibility of constructing a robot with the same manipulation abilities as a human, which could be operated remotely to perform a task deftly and safely.

Shadow is currently working on the commercialization of this system, which requires development of supporting infrastructure as well as bringing to production advanced robotic systems. Shadow has developed a new Modular Grasper with "Smart Grasping" (the right panel of Figure 3-2) capability based on the software and systems technologies behind the Dexterous Hand, and this is being tested on customer problems in industrial.

Table 3-1: A comparison between different SoA robotic grippers available in the market.

Company /Project	Product name	REFERENCE	WEIGHT (Kg)	DOFs	DOMs	FINGERS	MAX SPAN (mm)	PAYLOAD (Kg)	TORQUE (Nm)	GRIP FORCE (N)	SPEED (º/s)
Barrett	BH8	http://www.barrett.com/products-hand.htm	0.98	4	8	3	315	6	-		90
Kinova	KG-3	http://www.kinovarobotics.com/innovation-robotics/products/grippers/	0.73	3	6	3	175	-	-	40	-
kinova	KG-2	http://www.kinovarobotics.com/innovation-robotics/products/grippers/	0.56	2	4	2	175	-	-	25	-
On Robot	RG2	http://onrobot.dk/Product.html	0.65	-	-	2	-	-	-	40	-
Robotiq	3 Finger Gripper	http://robotiq.com/products/industrial-robot-hand/	2.3	1	9	3	155	10	1.7 - 7	15 - 60	90
Schunk	SVH	http://mobile.schunk-microsite.com/de/produkte/produkte/servoelektrische-5-finger-greifhand-svh.html	1.3	9	20	5	155	-	0.76 - 1.66	-	83-164
Schunk	SDH	http://mobile.schunk-microsite.com/en/produkte/products/sdh-servo-electric-3-finger-gripping-hand.html	1.95	7	7	3	215	-	1.4 - 2.1	1.3 - 2.0	210
Shadow	SGS	https://www.shadowrobot.com/smart-grasping-system/	2.7	9	9	3	300	3	2 - 3	10 - 20	120

Grasping and Manipulation are simple tasks that are taken for granted. The tasks that the humans think are easy to achieve are challenging for the machines to replicate, for example it is incredibly difficult for a robot to pick up an object and hold it steady. Therefore, humans in factories perform the tasks that require high dexterity and manipulation skills. Once the task gets repetitive, several other factors like fatigue, boredom, etc., creep in reducing the performance levels of humans as the day progresses in the factories. Currently, several robotic grippers are commercially available in the market (Figures 3-3, 3-4, 3-5). Table 3-1 presents a comparison of specifications and performance of such grippers in the market.

Figure 3-3: Barrett – BH8 (left panel) and On Robot – RG2 (right panel)

Figure 3-4: Shadow – Smart Grasping System (left panel) and Robotiq – 3 Finger gripper (right panel)

Figure 3-5: Schunk – SDH (left panel) and Schunk – SVH (right panel)

The table shows that Robotiq, Schunk and Shadow's SGS top the charts in various features that the robotic grippers can offer. Robotiq is marginally lighter in weight when compared to SGS, it is under-actuated (low DOF) and the torque sensing is lower too. While Schunk matches the DOF with SGS, the torque and force sensing capabilities are limited when compared to SGS. Shadow's SGS is highly dexterous and has torque and force sensing capabilities at every join of the fingers. These features enhance the compliance and robustness and contribute to the adaptive grasping capability of the SGS.

Grasping and AI

While a different approach, that is widely being researched, is to use simple grippers but enhance the grasping capability using various AI techniques. Table 3-2 briefly summarizes some popular projects. Ocado is using computer vision to recognize the object that is being picked up and expects that in future the robot will learn to distinguish fruit ripeness through machine learning. At Kindred, the robots are using deep learning and reinforcement learning to figure out how much pressure they should use when grasping and how best to grab the various items in inventory. Amazon is organized a "picking challenge" every year inviting individuals, start-ups, academics and many others to demonstrate their skill at picking objects and also funding the winners to carry on their good work to be licensed to Amazon in the future. Dyson's robotic lab is researching on developing real robot platforms with computer vision and advanced 3D sensing capabilities. Lacquey, a food manufacturing company, is using 3D vision systems and machine learning software to carry out complex tasks with a variety of foods.

Shadow's hardware has been the 'go to' for dexterous manipulation tasks in use cases in various sectors like production & assembly lines, product testing in pharmaceuticals, etc. iQonic will offer an opportunity (i) to enhance Shadow's hardware to handle macro and micro electronic parts, (ii) to integrate AI and other technologies to solve use cases and (iii) entry into opto-electronics market.

Table 3-2: Ongoing development projects of SoA robotic grippers.

Company	Project/Product name	REFERENCE	
Ocado	SOMA Project	https://ocadotechnology.com/tag/soma/ http://www.bbc.co.uk/news/technology-38808925	Online grocer Ocado has shown off a soft robotic hand that can pick fruit and vegetables, without damaging them, in its warehouses. The firm has an automated warehouse in Andover, Hampshire, where robots select crates containing specific items that make up customer orders.
Kindred	Kindred Sort	https://www.technologyreview.com/the-download/609209/kindred-robots-are-learning-to-grab-and-sort-clothing-in-a-warehouse-for-the-gap/	By **pairing AI with remote human operators**, the Kindred trial is using the operators' skills to further train the machines, while also allowing a small team of people to run operations around the world The robots are using **deep learning and reinforcement learning** to figure out how much pressure they should use when grasping and how best to grab the various items in inventory
Amazon		https://www.amazonrobotics.com/#/ https://www.bloomberg.com/news/articles/2017-07-27/amazon-enlists-researchers-to-build-box-packing-robots	Amazon "picking" challenge
Dyson	Dyson 360 eye – Vacuum cleaner robot	http://www.imperial.ac.uk/dyson-robotics-lab/research/	How can we use **computer vision** to enable a mobile robot, equipped with a camera, to actively explore a scene and understand its surroundings in usable 3D detail? The state-of-the-art in real-world mobile robot manipulation is severely limited by the lack of integrated research on advanced **3D sensing** coupled with real robot platforms
Lacquey		https://www.technologyreview.com/s/537646/robots-start-to-grasp-food-processing/	1. Robotic system that can grasp a chicken carcass moving along a production line and cut the shoulder tendons in preparation for the removal of the breasts and wings. That system can already match the average yield of a human worker. 2. In a second project, a low-cost two-armed robot called Baxter, produced by Rethink Robotics and designed to work safely alongside humans, is being programmed to place poultry carcasses onto the cone-shaped holders that carry them through a processing plant.

3.13 Dynamic reconfiguration of tools in handling and assembly (FICONTEC)

The assembly machines developed and sold by ficonTEC can generally be grouped into two different types:

- The first type of machine is highly specialized for the assembly of one single product. This machine type is optimized for single alignment/assembly step, e.g. the attach of a single lens by active alignment. Typically, the most critical requirements from customers are the yield and the assembly timer per component. If the product requires several assembly steps, then so called assembly lines are employed. These assembly lines consist of different assembly machines, each one optimized for one single task, which are connected to each other via conveyor system. As these machines are performing the same task all the time no need for a reconfiguration of tools is required.

- The second type of machine is much more flexible and can be used for several very different assembly steps. These machines can for example actively align a lens in front of a laser while at the same time passively solder a laser diode to a heat sink. The drawback of the flexibility is the increased cycle time for each step. These type of machines are typically used by universities, research centres as well as companies, which have a large variety of products with limited number. As this machines need to assembly several completely different components the work holder as well as the handling tools need to be changeable in a short time.

As state-of-the-art so called automated tool changers are used in several machines. These tool changers have a standardized interface which allows to transfer electrical signals, vacuum and pressurized air. Figure 3-6. shows the two most commonly used interfaces from Schunk.

Figure 3-6: Standardized interfaces for automated tool changers from Schunk (SA-005 left and SWK-001 right)

Onto these interfaces different kind of handling tools are mounted. The variety of tools may range from simple vacuum pickup tools (transfer of vacuum via the interface), via pneumatic grippers which can apply strong forces (pressurized air transferred) up to very fragile tweezer like grippers which are used for picking up tiny laser diodes with several hundreds of micron size (electrical signal transferred). For all these gripping tools no sophisticated feedback like a control of the holding force is possible.

Within a fully automated assembly process these tools can be changed automatically by the machine without any operator interference. As the exact position of the tool may be slightly different after each change, an automated calibration process needs to be applied. Generally, this changeover is not very complicated, however, it adds some time to overall cycle time of the assembly process. The tools on the tool changer need to be specially designed and matched to the individual components, which need to be handled. Including design and procurement the time until a new tool is available easily can be in the range of 2 – 3 months.

Within the iQonic project a highly flexible grasping hand will be developed by Shadow Robots. This hand would be able to not only be used for one single component but would allow picking up several objects with completely different form factors and weight. In addition, the hand will be equipped with multiple sensors so the gripping force can be monitored and controlled. This can be a very important property as several of the objects which are handled are very tiny and fragile.

Such a flexible grasping hand would allow using only one tool for multiple components and hence removing the need for changing the handling tool in an automated assembly process. This would not only reduce the cycle time but, via the implemented sophisticated sensors, also improve the handling of the components and hence increase the yield of the assembly.

3.14 Discrete event modelling and real-time prediction of KPFs (BRUNEL)

A zero defect manufacturing strategy in the case of manufacturing optoelectronic devices requires precise understanding of the process and the evolution of material, positioning of components and treatment of final output. In addition, high dexterity and flexibility in the electro-mechanical components of the machines tools in the manufacturing process are the capabilities required.

The knowledge accrued by understanding the condition of process and the adaptability of machine tools will enable us to deploy advance learning techniques and artificial intelligence to model the manufacturing process and actively discover production process anomalies and predict potential defects. The analysis will describe the causal relationships between defect types and the events leading to them, which will eventually lead to active and predictive corrective actions during the production life cycle.

Defect prediction will also have severity stratification based on circularity-sustainability context, where online decisions are made on to whether or when to remove the job from the production process, so that there is a maximum likelihood for recyclability or reuse of the material. Therefore, efforts will be made to firstly create a complete tools and machine:

- capability and specification record (automatically updated at specified intervals) resulting into a gap identification of the current capabilities and the ideal (i.e. beyond the SoA),
- condition and state analysis (sensors and actuation),
- expert knowledge and interpretation of states related to machine performance and quality control.

Secondly, material monitoring and analysis:

- The specifications of the raw material (assembly and building components).
- Online sensing and actuation technology and requirements that provides the necessary information on the evolution of material and quality loss/gain throughout the production life cycle.
- Flow analysis.

The data obtained from the shop floor will then be utilised to build the control and decision optimisation functions. The combined knowledge and capability of consortium as well as the inclusion of OEMs in the project will enable the Data Analytics and the Monitoring and Control engineering rules and planforms to be implemented in actual use cases and results to be observable. Through the observations the gaps between the actual and ideal will be filled and implemented on a live and working platform, leading to validation and verification of KPI models and DSS methodologies.

The developed innovative discrete event modelling solution combines historical data and real-time data extracted from the manufacturing line providing a real-time and predictive model, highly efficient clustering (DBSCAN etc.), adaptability on manufacturing lines, and fast predictions with a small margin of error (less than conventional methods)[55] [56]. All these properties are SoA in the field of zero defect manufacturing or micro-manufacturing including micro-optics and no similar solutions exists in these fields.

[55] Tavakoli, S., Mousavi, A., & Broomhead, P. (2013). Event tracking for real-time unaware sensitivity analysis (EventTracker). IEEE Transactions on Knowledge and Data Engineering, 25(2), 348-359.
[56] Danishvar, M., Mousavi, A., & Broomhead, P. (2018). EventiC: A Real-Time Unbiased Event-Based Learning Technique for Complex Systems. IEEE Transactions on Systems, Man, and Cybernetics: Systems, (99), 1-14.

3.15 Adaptive optics for inspection and quality control systems (FORTH)

As far as optical detection of critical defects (e.g. in wafers) is concerned, the key developments that will advance the in-situ quality measurements, as well as the inspection accuracy of the positioning, during the assembly processes of the iQonic project would be:

- the definition of the critical defects,
- the optical identification and evaluation of the critical defects,
- the precise calculation of the optical parameters, that concern the accurate inspection of the parts positioning,
- the improvement of the spatial resolution in the optical inspection of the parts positioning from some micrometres nowadays, to the sub-micrometre level.

Adaptive laser optics could provide feedback in the process flow and in the in-line inspection of the materials assembly and manufacturing parameters. To evaluate with high precision the material parameters (e.g structure, roughness thickness, and porosity) during the process, diffraction limited resolution is required. Experimentally, the diffraction limited resolution is compromised due to aberrations. In order to solve this problem, state of the art hardware-based adaptive optics could utilised to compensate for both the optical setup and sample aberrations. To mitigate complexity of the opto-mechanical system and related electronic control required by hardware-based adaptive optics latest studies utilize digital adaptive optics (DAO) in wide-field imaging systems. By using DAO, the hardware pieces such as the wave front sensor, deformable mirror, and coordination between them, are eliminated. This allows in more flexible optical setups yet to be demonstrated in an optoelectronic devices production line.

Nowadays, in-situ and in-line inspection of optoelectronic components and devices during manufacturing and assembling, is mainly based on optical imaging. The optical imaging is inevitably subjected to aberrations that hamper the image resolution and consequently bias the available information that could be extracted. To this end the iQonic consortium could advance the SoA by predicting, evaluating and correcting the optical aberrations present in a production line (according to the end users), using adaptive optics.

3.16 Gluing and soldering processes of optoelectronics for prototyping (TAU)

The bonding stage affects to alignment accuracy and precision as well as reliability, and the performance of assembled micro-optics assemblies. Therefore, the bonding stage is one of the most critical and demanding part of micro-optic assembly processes. Various different bonding techniques have been used in micro-optics in the past as described earlier in Section 2. The SoA bonding techniques can be divided into three categories:

- gluing with UV-adhesives,
- soldering,
- welding.

The performance and the reliability of gluing is dependent on the gluing process and the used materials including the UV-adhesive. The SoA systems use low shrinkage UV-epoxies (typical commercially available epoxies have a shrinkage in the range of ~3-5%). The inevitable shrinkage of UV-adhesives induces stress that may lead long-term reliability and performance issues. To overcome these issues, ultra-low shrinkage (below 1% shrinkage) UV-adhesives are developed[57] as well as in-situ adhesive shrinkage measurements[58]. Micro-optic bonding with UV-adhesives has also other known issues such as the large coefficient of thermal expansion (CTE) mismatch with the substrate and the bonded components, relatively low bond strength, and outgassing which continues after the curing process. Despite its drawbacks, UV-bonding is a fast and low cost method allowing adapt large mechanical tolerances and various material interfaces. Moreover, UV-bonding can be applied for components requiring low bonding temperatures.

[57] Bachmann, A. (2001, November). Advances in light curing adhesives. In Optomechanical Design and Engineering 2001 (Vol. 4444, pp. 185-196). International Society for Optics and Photonics.
[58] Lewoczko-Adamczyk, W., Marx, S., & Schröder, H. (2017). Shrinkage Measurements of UV-Curable Adhesives: An elegant method based on a laser distance sensor for in-situ measurements of the polymerization shrinkage. Optik & Photonik, 12(4), 41-43.

Flux-free soldering provides high mechanical stability, high thermal conductivity compared, and very low outgassing rate. Since the performance and reliability of high-power active optoelectronics are strongly affected by thermal management and heat dissipation issues, soldering provides often the best compromise between the performance, manufacturability, and costs compared to other bonding techniques. Reliability of optoelectronic component is often linked to its operation temperature that can be addressed with low thermal resistance packaging reducing rate defects deteriorate component performance. On the other hand, there are various requirement for a soldering process including good wettability between the bonded component and the substrate, low CTE mismatch, no long-term solder deformation, and some of the components may require low soaking temperatures and low electrical resistance. Indium and eutectic gold-tin are the most commonly used solder materials for RoHS compliant optoelectronics. Pure indium has a low melting point and it is a ductile material and therefore it can relief the thermal stress caused by the CTE mismatch between the substrate, solder, and the component but it can also suffer from thermal fatigue and electro-migration in high-power applications. Eutectic gold-tin is a hard solder, low oxide formation, high mechanical and thermal stability, but since eutectic AuSn solder has high strength a significant CTE mismatch may cause cracks over thermal cycles. Many solders have been considered to meet the complicated and often contradicting requirements of solder materials[59] but the industry is still searching an option that could provide a good compromise between the indium and gold-tin based soldering technologies. Moreover, different substrate or carrier materials, where devices are bond play crucial role in reliability and performance of the optoelectronics assembly. Use cases dictate different substrate requirements for thermal and electrical conductivity, CTE value, mechanical rigidity and other aspects.

The iQonic consortium will investigate solder and substrate materials and develop ultra-low defect rate bonding processes that can adapt the varying requirements of active and passive components in micro-optic assemblies in different user cases. Furthermore, iQonic consortium is targeting to develop ultra-low defect rate self-aligning soldering processes to enable passive alignment of micro-optics components for micro-optic assemblies in which active alignment is not available due technical or economical reasons.

3.17 Metrology enhanced tooling for UV-gluing (TAU)

Despite the development of passive and active alignment systems over the years, the assembly processes requiring the tightest post-bond alignment tolerances are still challenging even for SoA assembly stations because of various sources causing random and systematic alignment errors. One of the main issues in the assembly processes employing UV-adhesives is the inherent adhesive shrinkage that leads to post-bond accuracy and precision degradation. The present SoA assembly processes use epoxy, acrylic and silicones based UV-adhesives. Epoxies have relatively small shrinkage but they have long curing time. Acrylics, in turn, have short curing time but larger shrinkage. Silicones are not usually used for processes where high post-bond accuracy is needed since these adhesives will lead to quite poor mechanical stability, but on the other hand silicones have good thermal properties.[60]

Even though the shrinkage and dosage of the UV-adhesive have significant role in the post-bond alignment accuracy, it is rare that commercial SoA micro-optic assembly stations will verify or accurately measure the movement of components during the UV-curing stage. Moreover, the shrinkage measurement after the bonding process may be difficult[61]. Hence, fast in-situ shrinkage measurements could help to pre-compensate the volumetric shrinkage of UV-adhesives. Such ability can be used to improve the quality control and determine the possible shrinkage variations during the curing but also to make faster prototyping as time consuming iterative glue shrinkage tests can be avoided. Some research studies have been carried out to implement the in-situ shrinkage measurement of UV-adhesives based on volume measurements[62] and laser distance sensor[58] for example, but not many if none of these solutions have been integrated with assembly stations to the best of knowledge iQonic partners. The iQonic consortium will improve the SoA by developing an insitu shrinkage measurement system based on laser interferometry that will be integrated with an assembly station.

[59] Suganuma, K., Kim, S. J., & Kim, K. S. (2009). High-temperature lead-free solders: Properties and possibilities. JOM Journal of the Minerals, Metals and Materials Society, 61(1), 64-71
[60] Kożak, M. M. (2005). Development of thulium-doped fluoride fiber amplifiers. Cuvillier Verlag
[61] Müller, Tobias, et al. "Customizable assembly solutions for optical systems." High Power Diode Lasers and Systems Conference (HPD), 2015 IEEE. IEEE, 2015.
[62] Schoch Jr, K. F., Panackal, P. A., & Frank, P. P. (2004). Real-time measurement of resin shrinkage during cure. Thermochimica acta, 417(1), 115-118.

4 The Demonstrators

The capacities of the iQonic platform will be demonstrated with four use cases. In this section, these use cases will be described and the project developments are linked to the demonstrators.

4.1 ALPES

ALPES has three areas that will be used to test the iQonic solution. These technologies are described in the following subsections.

4.1.1 Front-end mapping

In the field of Quantum Cascade Laser (QCL) manufacturing technology there are still challenges to overcome and it is common to have defects on the fabricated wafers. Early detection of defects at various production stages from epitaxial growth to chip assembly and aggregating information into a wafer map is crucial to limit waste of resources and ensure timely delivery of products.

Potentially non-working devices that can be sorted-out before die-bonding and testing save material and operator time. For example, the detection of a hard-mask with strain or adhesion issues prior to etching enables to re-define the hard-mask and recover the wafer. A problem detected prior to the MOCVD lateral regrowth, in turn, enables to scrap the wafer before the expensive regrowth and device processing and thus limit cost.

Currently, defect mapping is sometimes done visually by operators but is takes very long time (several hours). Therefore, defect mapping is not completely integrated into the fabrication process and it is used only occasionally. Systematically conducted defect mapping integrated into the production chain enables to make advanced performance analysis after the defect mapping data is combined with other measurements conducted by ALPES.

A possible development is to have FORTH's adaptive-optics setup inspect wafers at various stages during front-end processing, combine this data with other information we are already getting and aggregate the data in a wafer map.

Later on, after cleaving of the lasers, FICONTEC's pick-inspect-and-sort tool could be used to sort all the devices from a wafer in different categories and do further characterization (waveguide profile measurement).

Simple DSS would probably be sufficient to eliminate lasers with defects or put them into categories.

4.1.2 Systematic ALT screening

Since the demonstration of QCL devices in 1994 just a few studies have been performed regarding the lifetime QCLs. In the QCL community, the general understanding is that the mechanisms influencing the lifetime of these devices are fundamentally different from those associated with laser-diodes emitting at much shorter wavelengths and working on electron-hole recombination across a direct band-gap (where the failure modes have been studied extensively given the large spread of laser-diode applications). For example, the catastrophic optical damage (COD) that is a well-known failure mode in laser diodes is not present in QCL devices. QCL devices fail as well, obviously, but the failure modes are usually attributed to the epitaxy quality and device processing that is not mastered as well as for high-volume laser diode market.

Nevertheless, the lack of lifetime studies does not increase the confidence of decision makers that are evaluating the integration of QCL devices in larger volume applications (> 100 pieces).

ALPES plans to introduce a systematic accelerated-lifetime-testing (ALT) for each wafer coming from front-end processing in order to rule-out defects that reduce the lifetime and that could remain undetected with the current entry-inspection and to generate systematic data related to the QCL device lifetime.

There is a study published in 2016 regarding the lifetime of QCL devices[63]. However, the iQonic consortium is not aware whether any systematic lifetime measurements have been carried out on fabricated wafers. The spectral range between 4 µm and 12 µm where ALPES produces QC lasers is huge and about every spectroscopic application requires a specific wafer. Moreover, wafers are sourced from various epitaxy foundries that then are processed at different fabs using their specific recipes. Therefore, in principle, each wafer fabricated with a different configuration should go through an individual ALT test in order to rule-out defects that affect device lifetime and are associated with the given configuration. Furthermore, this will allow to study lifetime issues extensively and increase system-integrators confidence into the devices.

4.1.3 COS assembly and pre-testing automation

Currently ALPES's assembly chain is entirely manual and the different assembly steps are executed by operators or outsourced to suppliers for larger series of devices (> 100 devices). The reason for this is that our typical client order is a relatively small number of devices with identical specifications and the devices have geometry variance between each other. In the present assembly chain, trained and highly experienced operators provide the required flexibility to adjust the assembly chain according to geometry variations. The manual assembly process is time consuming and as the assembled wafers arrive to ALPES in batches, this can lead to very un-balanced mounting queue in time with extreme peaks just after the wafer reception. Consequently, depending on the priority of a given wafer, the lead-time for a given sample can become unnecessary long.

QC lasers are edge-emitters enforced by selection-rules of quantum mechanics and therefore the lasers need to be cleaved in order to test the device. Moreover, QC lasers are known from their large heat-generation (the injection current densities are 10-100 times larger than for standard laser diodes in VIS or NIR range). Hence, high-quality device mounting is vital for these lasers and therefore potential devices for a specific client are first cleaved and mounted on an AlN sub-mount before testing can be performed.

The current manual mounting process is very time consuming. An automated equipment that is capable of soldering the laser chip onto an AlN sub-mount and perform the visual inspection of device facets would drastically decrease COS assembly time per sample. This would lead to a significant reduction of the lead-time to ship the devices to the customer. An automated mounting equipment would also ensure constant high-quality bonding and thus reduce variability in the device performance. The automated in-situ visual inspection of device facets would enable a much tighter feedback for the front-end processing and the device performance analysis enhancing our knowledge on fabrication processes and predictability. Automation could also increase the device throughput.

4.2 PRIMA

Being a semiconductor, diodes productions are typically vertical, with very high investment costs and are located especially in countries with an emerging economy, such as China or India. Many of the diode assembly and packaging operations are still manual. In fact, the production of this component is carried out in countries where the cost of labor is very low. In this sense, the reliability of the component and the certification are also affected.

Every modification requested by the diode manufacturer requires an increase in the production cost causing an increase of the final price of the diode up to 10 times compared to the standard product and delivery times even for several months of waiting. The start of production for custom versions and for new product versions, such as direct high-brightness diodes, is very expensive and the time to market of new products in this category is very long.

Today, Prima's production chain of the laser source is highly vertically integrated, so it is difficult to track data and exchange information, and this leads to high time to market and a slow service reaction for the end user. The fragmented production causes also difficulties in customizing the product, due to an information gap between diodes manufacturers and the end users with specific application. Also, the final campaign of tests is important to verify the target performance measures and reliability of the product. This inspection stage is currently a time consuming and expensive stage, performed only at the end of the packaging process, where

[63] Xie, F. et al. ; Long term reliability study and life time model of quantum cascade lasers, APL 2016, 109 :12

product repair and reuse options are not feasible anymore. Furthermore, high operating costs and investments for specific equipment to be used strongly affect the unit cost of the diodes. The raw material has a non-negligible effect on the cost as well, because it mainly consists of rare earths that are usually provided by extra-EU countries and are characterized by high value fluctuation of the market. These cost constrains, reinforce the vertical integration disadvantages and lead to a high cost of the laser source. In particular, nowadays the diodes manufacturing process makes up the 60% of the total cost of the laser.

The solid-state laser sources like those produced by Prima Electro for Prima Industrie laser machines, are made according to the following scheme:

- A number of Fiber Laser Modules (FLM) as shown in Figure 4-2. Each laser module consists of multi-emitter diodes combined with each other through first-stage combiner and the so called Optical Engine which consists mainly of the active fiber and the Bragg gratings mirrors. Each module ranges from 400 W to 2 kW;
- Output combiner or second stage output combining the different modules to achieve a power of many kW with a high brightness laser beam quality;
- Control electronics for the individual modules and the laser source;
- Laser beam delivery fiber.

Figure 4-1: A typical laser module fabricated by Prima.

The creation of a laser source requires the use of multi-emitter diodes. The multi-emitter diode is a very complex component and requires knowledge and design practice in the field of photonics and electronic micro-nano. The size of this single component is a few centimeters and inside it are allocated the individual emitters whose magnitude is comparable with that of a 1 cent coin.

The main object of this case is the high power laser diode on gallium arsenide semiconductor substrate (GaAs), emitting laser radiation around the 900 nm.This component must have excellent reliability and brightness characteristics for material processing applications. The individual devices must provide an optical power of about 15 W and are mounted on a support (called "carrier") with low thermal resistance (referred to as "Chip-on-Carrier, CoC"), in order to be integrated into modules in able to supply 100 W in fiber.

Currently, Prima uses a high precision robotic cell with automatic self-reconfiguration for laser diode packaging but the existing assembly line and the process chain still require optimization in various areas:

- The main themes that interest PRIMA in this project are the local monitoring of the assembly process and the global monitoring of the diode module production. The goal of Prima is to achieve a zero defect manufacturing process chain that utilizes the collected data generated by advanced monitoring systems.
- Improved traceability would allow tracing data from the starting wafer to the final product. Traceability also enables to intervene problems that relate to the production line or to the intrinsic characteristics of the wafer. Improved traceability would therefore allow to understand better where the problem was born and to act directly where it is needed.
- Real-time monitoring, early stage defect detection, CPS, and RSC would enable the possible disassembly, regeneration and re-use of components. Currently, these aspects are not managed due to vertical production and high operating costs.
- Fast in-line inspection would avoid the costly steps that are performed at the end of the packaging process in the existing assembly processes. Moreover, in-line inspection would enable to detect faulty

components and assemblies, giving a possibility to intervene where necessary. Therefore, fast in-line inspection could lead to material and production time savings.

- Rapidly reconfigurable assembly line would shorten the setup time of each changeover between two different types of products. Hence, easily reconfigurable assembly system could save capital and operating costs and give the ability to reach customers with different needs.

4.3 FILAR

FILAR is a company that fabricates many different types of synthetic crystals for various applications. The production chain of FILAR includes the crystal growth, drilling, polishing, coating, and quality control stages. This production chain would greatly benefit from fast and accurate process parameter online adjustments and insitu measurements that could verify the bulk material quality, dimensions, and geometries of crystals. FILAR’s production chain is also requiring a quality control system that identifies the possible crystal residues after cutting, drilling, and polishing stages.

In the present production chain the process quality control is carried out partly online and partly offline and the production chain does not provide enough feedback to accurately inspect the optical, geometrical, or functional properties of crystals and therefore the present system cannot predict or even detect possible defective components during or after the fabrication process stages. However, iQonic solutions will demonstrate its capabilities by employing an integrated smart sensor network and visual inspection methodologies to rapidly adjust the process chain, identify possible defective crystals in the different parts of the production chain and reuse these components after the crystal requalification. The iQonic solution expected to result in significant reductions in material waste and process adjustment times.

Furthermore, a system integration of FILAR’s crystal material is planned in iQonic, which opens up new oppotunities for the company. Processing thin disks of a doped crystal material by means of iQonic enhanced lapping and polishing processes will allow partner Fraunhofer to bond the thin disk to a heat sink. This assembly can be characterized by partner Hilase for high power laser applications.

4.4 BRIGHTERWAVE

Brighterwave is concentrating on two product portfolios in the project: (1) lasers for life science applications and (2) RGB lasers for AR/VR applications. In both application areas, laser diodes generate light, which may be coupled with nonlinear crystals for frequency conversion. Moreover, the micro-optic assemblies include optical lenses, filters, and particularly in application (1) the modules may also contain optical fiber(s). The accuracy and repeatability of the alignment in the assembly process of the fastened components are the key development points.

The current fabrication chains of the modules comprise multiple disjointed assembly steps with varying component geometries and placement precision requirements. The iQonic consortium can improve the current assembly process in different ways. The interference engine and assembly process design will be used to optimize the multi-stage assembly process. Sensors network, IoT, and data management middleware can provide feedback and statistical data from the assembly steps and detected defective components. The collected information can be analysed and used to adjust the process chain to improve the KPIs for varying geometries and precision requirements. Smart tagging based algorithms are also expected ease the component identification and enable automatic parameter loading for each component during the various stage of assembly processes. Therefore, smart tagging increases the reliability and adaptability compared to Brighterwaves’ current assembly processes. The iQonic solution also enables the early stage identification of defective components, prevents defective components propagating in the value chain, and essentially minimizing the production costs and maximizing the throughput employing CPS and DSS modules to determine the optimized process flow in terms of costs after a defective component is detected. This is especially important in the demanding application (2) in which consumer market is targeted.

4.5 Technology roadmap

In this section the presented iQonic technologies are linked to the use cases. Table 4-1 indicates how each of these technologies are demonstrated and what uses cases reflect the development of each technology in the project.

Table 4-1: iQonic technology roadmap

iQonic Technology	ALPES	PRIMA	FILAR	BRIGHTERWAVE
Assembly process design, analysis, and optimization	x	x	x	x
Decision Support System (DSS)	x	x	x	x
Reverse supply chain (RSC)	x[1]	x	x	x[1]
Middleware	x	x	x	x
Knowledge based system (KBS)	x	x	x	x
Early detection and prediction engine	x	x	x	x
Smart tagging	x	x	x	x
Sensor distributed network	x[1]	x	x	x
3D-inspection methodologies	x	x	x	x[1]
Electronic nose	x[1]	x		x[1]
CPS	x	x	x	x[1]
Smart grasping hand	x[1]		x[1]	
Dynamic reconfiguration of tools	x	x		x
Discrete event modelling and real time prediction of KPF's	x	x	x	x
Adaptive optics	x	x	x	x[1]
Gluing and soldering processes of optoelectronics for prototyping	x[1]	x[1]		x
Metrology enhanced tooling for UV-gluing		x[1]		x

[1]The technology could be useful for the use case but more analysis is needed to verify the practicality of the technology to the use case.

5 Conclusions

The assembly of micro-optical systems creates many challenges to the industry, which tries to find cost-effective solutions for high accuracy and precision requirements, small component dimensions, and increasing production volumes and quality requirements. To solve these challenges the iQonic consortium will develop many different technologies and create a versatile and scalable zero-defect platform for micro-optic assembly processes.

The iQonic solution will improve the SoA in the field by in many ways. The consortium will optimize the full process chain in terms of performance, reliability, costs taking into account non-idealities, and stability issues over the assembly lifetime. The iQonic solution will be integrated with intelligent data acquisition and analysis systems (e.g. sensor distributed network, KBS, 3D-inspection methodologies, electronic nose, adaptive optics) that can monitor the full assembly process chain and both identify (Middleware) and predict (early detection and prediction engine, discrete event modelling and real-time prediction engine) possible defects. Based on pre-determined rules, DSS will control the process chain and employ CPS and RSC to re-qualify potentially re-usable components in the assemblies. The iQonic solution will also use smart tagging to enable new functionalities in micro-optics assemblies such as automatic parameter loading, time stamping based on the production phase, and the adaptation of the production line according to the components and semi-products. The other functionalities of the platform will include a smart grasping hand that increases the flexibility of the gripper technology, and dynamic tool reconfiguration that enables fast and fully automatic changeovers between different products. The iQonic consortium will also develop advanced gluing and soldering technologies to improve reliability, performance and cost efficiency.

Some of the key iQonic technologies are new elements in both optoelectronic assemblies and in the quality control of manufacturing industry such as electronic nose, adaptive optics, and real-time prediction engine. Most of the technologies are already applied in different fields of manufacturing industry such as RSC, CPS, early detection and prediction engine, smart tagging, metrology enhanced tooling, and automatic 3D-visual inspection methodologies, but these technologies are not used (or are rare) in today’s SoA micro-optic assembly processes. Moreover, for example KBS is not common in manufacturing industry. During the project, iQonic consortium will improve and introduce new features to these technologies.