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A refractory engineering program for the 21 st century

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ABSTRACT

The Federation for International Refractory Research and Education (FIRE) has been conceptualized twenty years ago. At the time, its purpose was to maintain the training of graduated engineers to enroll and to adapt to the new business plans in the refractory industry. It was the blooming of the Information Age, of the knowledge workers.

This paper is about the need to adjust to a new era, knowing that the benefit of education prime value is its long-term value. To have an outer and an inner vision about innovation, the first part of the paper is concerned about how do we learn and how our brain rules. In the second part we try to anticipate the customers' needs trying to surf with them on the Ecology wave, including the Environment, Energy, Economy, and Ethics other waves.

Accepting that this is already brewing at an accelerated rate, the conclusion is that FIRE and the other educators need to continue mimicking the CDIO (Conceive Design Implement Operate) approach which has inspired us for the last 20 years, for another 20 years, to adjust to the Conceptual Age in order to educate the creators and the empathizers who will direct the flow, in the refractory industry.

1. Introduction

A consolidated refractory education program following a CDIO approach at the M.Sc. and Ph.D. levels must emerge for two reasons:

1 To grasp with the anticipated changes our world will have to face in the next 20 years (ecological, economical, energetical and social) and
2 To stay in tune, with all the indicators which are alerting us, with the fact that a new mind set is now required to move from the Information to the Conceptual Age as illustrated in Fig. 1.

At first, it is essential to focus on the need of our industry to recruit the human resources require to go surfing on the Eco-Design of Refractories Wave (the theme of this issue). It will be necessary to seduce and then to train young engineers to manufacture products in reducing-reusing-recycling all the resources needed. Then in order to promote the implementation of the required educative structure, the conjugated efforts of 3 types of actors are necessary:

1 *Educators*(administrators and professors) will have to change their mind set. They need to become mentor rather than instructor to transmit information (part of such a function will be challenged by machine learning programs in virtual surroundings). It will require leadership with empathy to train the graduate students into more creative thinking;
2 *Industrial researchers* (and administrative managers) will have to obtain the freedom to work within various networks, to be confronted with a diversity of expertise, including technical, social and cultural aspects, keeping in mind the value of intellectual property of their own company;
3 *Students* (at the graduate levels) have also to be eager to immerge into more than one environment of study, volunteering to travel to acquire both the local and the global vision of the world in which they do need to contribute.

Each kind of actors will have to learn new roles to move from the Information Age to the Conceptual Age. At first, it is essential to focus on the need of our industry to recruit the human resources required to train more Right-Directed-Brainers (RDB vs. LDB). Hence the paper is divided into four parts.

The first part provides a simplified image on how the brain rules. The second part is about left and right-directed brainers (RDB and LDB) using objective and subjective knowledges. In the third part, a short

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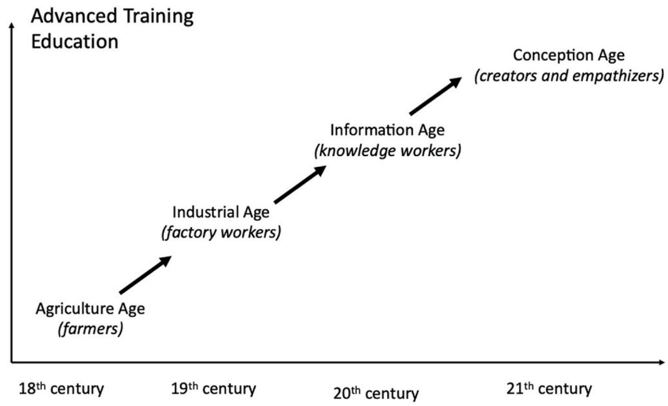

Fig. 1. From the agricultural age to the conceptual age [1].

review of what is the CDIO's approach, which did influence the FIRE Education Programs since its beginning. In the fourth part are then described four recent initiatives, to measure what remains to be done before the midst of the 21st century to stay in touch with the announced changes of paradigm:

1 The FIRE Summer Schools, under the leadership of Orléans University (France).
2 The FIRE extended roles in participating into broad international projects, under the leadership of the CEC, University of Limoges (France).
3 The FIRE Educative Platform, under the leadership of RWTH Aachen University (Germany).
4 The FIRE initiative to develop data mining and data management skills, under the leadership of The Federal University of Sao Carlos (Brazil).

2. The brain rules

The human brain may be divided into three parts, the fore-brain, the middle brain, and the hind-brain [2].This latest part is the primitive brain which contains the cerebellum. The mid-brain is a relatively short and narrow region connecting the fore-brain and the hind-brain to the spinal cord. The fore brain is the largest part of the nervous system in humans, further subdivided into the cerebral cortex (with its gray and white matter), the thalamus, the hypo-and the epi-thalamus. The mid-brain is a relatively short and narrow region connecting the fore-brain and the hind-brain to the spinal cord. The hind-brain is the most evolutionarily ancient part of the human brain resembling to a reptile brain. It controls the basic bodily functions necessary for survival, such: as respiration, blood pressure and heart rate. Globally the brain is a network of nervous cells made of 10^{15} connections between 10^{11} nervous cells and 10^{4} neurons and synapses. The brain controls the three human nervous systems: the central nervous system, the peripheral nervous system, and the somatosensory nervous system. All three systems send signals to different parts of the brain, in total in 52 different zones, 47 of them being detectable in the outer layer of the cortex. As shown in Fig. 2 the cerebral cortex contains most of the associations needed to carry-out, higher-order information processing to control our mental status.

Three additional functions – consciousness; emotions and droves – memory – act in conjunction on all systems, in a widely dispersed manner, specially at the highest level of processing information and encoding then in the proper zones. Those three functions also govern our mental status, so essential for everyone to learn, to develop the right awareness and attention. Those three functions involve many parallel pathways of the motor-sensory-somato sensory systems to process information occurring at the consciousness and unconsciousness level, motivated by drives, modulated by emotions invoking each time different type of memories.

"Memories may be defined as changes in behavior; stored in different zones, integrating new stimuli results, which then affect the function of the entire neuronal system and the whole-body behavior. It is accepted nowadays that memories do occur as a result of physiological and anatomical changes, and do influence communications; for instance, the explicit or declarative memory involves the conscious recollection of experiences". [2a].

So, yes, the brain rules but it has no access to absolute truth neither from our consciousness (or objectivity) nor from our unconsciousness (or subjectivity). It is then necessary to distinguish between objective and subjective knowledges to adopt then an *imaginative rationality* (to be defined later in section 3, about moving into the conceptual age.

Despite the progresses made in Cognitive Sciences, consciousness is still the most elusive of all brain functions and unconsciousness is not accessible at all. Again, sciences cannot pretend to have access to any

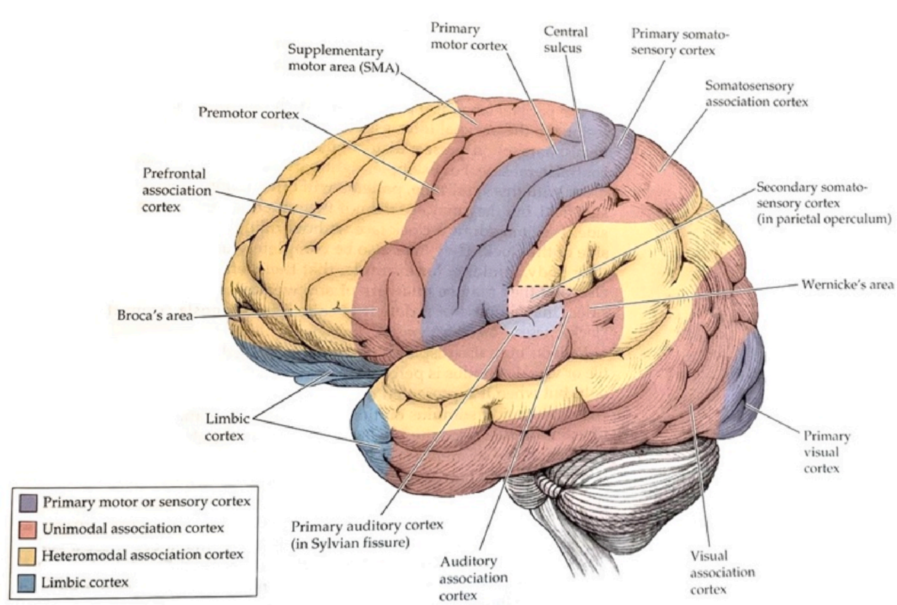

Fig. 2. Lateral view of left hemisphere showing main zones of primary sensory and motor cortex, unimodal association cortex and multimodal association cortex [2].

absolute truth.

We also accept, as a simplification, that objective knowledges are associated with the left side of the brain of LDB and the subjective knowledges to the right side of the RDB. The left side hemisphere of the brain is the rational, analytical, and logical part, and the right side, the nonlinear, intuitive and stories telling part.

Logic tries to generalize and to strip the decision making from its specific context, to remove from it subjective emotions and imaginations. The stories telling part is an important cognitive process which encapsulates information in a global context with desires, emotions, and imaginations. The LDB reasoning is sequential, in a cartesian manner, being dualistic, trying to treat only objective knowledges. The RDB reasoning is holistic, recognizing patterns, symbols, interpreting emotions and nonverbal expressions.

Automation, robotics, and artificial intelligence (AI) will affect the present generation of knowledge-white-collar workers in the 21st century as computers did for the blue-collar workers in the 20th century. New technologies can automate not just manual but also cognitive LDB tasks. Such tasks can be easily outsourced in different parts of the world at much cheaper rates. So LDB, must develop aptitudes that computers cannot do better, that is to act as creators, empathizers and meaning makers, and learn to collaborate with RDB, to obtain decisive roles in the Conceptual Age.

3. The objective and subjective knowledges to move into the conceptual age

Truth is always relative to a conceptual system, built-in a given brain. Although the brain rules, none of the humans have the same brain, wired in the same way. Therefore, there is no objective truth either. For many people trained in a dominant scientific culture, objective truth, based on sciences, is well accepted. Then for such persons to surrender to subjectivity (as it was in the Middle Age) is a nonsense. Between objectivism and subjectivism there is a third choice, trying to adjust to both. What is needed is the equilibrium between the objective and the subjective knowledges which each person has accumulated.

Objective knowledge refers essentially to scientific knowledges related to any material objects, with measurable properties in within the limits of the experimental tools available today. Subjective knowledge refers to intangible things or artifacts, as thoughts, moral values, rituals, and mysticism, which have been conceptualized with words and symbols, to acquire a spiritual meaning.

One approach worth considering is the imaginative rationality approach, as experientialist are using metaphors to bridge the gap between objectivists and subjectivists. As explained by G. Lakoff and M. Johnson [3]. "A metaphor unites reason and imagination. Imagination in one of its many aspects, involves using one kind of things in terms of another kind of things, what we will call *metaphorical thoughts or imaginative rationality*". Metaphor helps to comprehend partially what cannot be comprehended totally, such as feelings, moral and spiritual awareness.

Another approach has been suggested by S. Pinker in "The Blank State" is based upon Cognitive Psychology [4]. None of the authors of this paper being expert in such a scientific domain, it has been decided to follow the imaginative rationality approach as defined by Lakoff and Johnson.

With such a background it is appropriate to recall what the CDIO approach [5] is about and how important it is to train refractory research engineer LDB, to develop their personal and interpersonal skills, their creative thinking, and their right brain side aptitudes to move into the Conceptual Age, using their leadership and empathy, as well as RDB.

4. The CDIO (Conceive Design Implement Operate) approach

With a 20/20 vision FIRE was initially conceived in 2003 [6]. The concept was to create a Federation of refractorists grouping manufacturers, users, raw materials, and other service providers including academics to create an international pool of experts, working in a coopetitive spirit, (both collaborative and competitive manner) to define and to obtain financing to support educative and research projects.

The idea started to be cultivated during and after a session devoted to education, for the first time as part of a UNITECR meeting in 1997 [7]. It took another six years to crystallize with the insights of many industrial mentors, among them Landy [8], Eschner [9], Karuth [10]. The click, in 2003, came when, after 17 years of existence, the Industrial Chair on Refractories at Ecole Polytechnique (CIREP, 1986–2003) was confronted with the decision to cease its activities by 2005, at the latest.

This happened before knowing about the formalization of the CDIO approach,in order to rethink engineering education, which was published in 2017, essential to move in and participate into the Conceptual Age, as described in several papers [11–14], in between 2006 an 2015.

Conceive for the manufacturers means to develop the best business plans to satisfy the user's needs, considering the sciences, technologies, engineering, and mathematics accepted knowledges at our time (the STEM Core) to create a product which is not available in nature.

Design focuses on the plans, drawings and algorithms that describe the product, process, system to be implemented to seduce the customers.

Implement refers to the transformation of the design into the product including the hardware manufacturing and software coding, testing and validation.

Operate or organize is about how to use the implemented products, process, or system to deliver the intended value, including maintenance to better reduce-reuse recycle all resources.

CDIO as stipulated in Ref. [5,6] does fit with the Eco-Design of Refractories.The FIRE's educative credo is then: Education is about students learning by mimicking teachers (and industrial mentors) to acquire knowledge and to make use of:

- The rules of communication, induction (experimental and deduction (mathematical);
- The methods of production (practical);
- The methods of traduction and exchanges (economical);
- The laws of distribution and redistribution (political);
- The rules of seduction (ethical and ecological).

Engineering education is about students learning how to implement efficient changes at four levels:

- The technical efficiency (based on STEM core);
- The production efficiency (based on pragmatism):
- The organizational efficiency (based on management know-how);
- The economic efficiency (based on financial and political analysis)

Then FIRE 'students should be confronted with different aspects of:

- Knowledge discovery (a subject to be discussed in the next paragraph along with data mining.
- System thinking and discussion about the abstraction necessary to define and model systems and to use metaphoric thoughts, taking on account that the brain rules,
- Professional skills and attitudes to assert the social and technical impact of new discoveries and innovations.

Such courses would simply be selected from different Arts and Social University Department programs and adjusted to our discipline. The best solution of course would be for the refractory professors themselves to act as a mentor for such a purpose or experience team teaching with a colleague from any cognitive science faculty, psychology (of learning), linguistic, philosophy, neuropsychology, to experiment the value of interdisciplinarity or even multidisciplinary, using more of our right-side brain.

5. Some of the building blocks already in place

As its beginning FIRE network was able to initiate educative research projects for individual students who had in order to receive extra financial aids: i) To be able to communicate in English; ii) To volunteer to work under the supervision of two professors, on a project to be conducted on two campuses, to benefit from extended experimental facilities; iii) To learn eventually another foreign language; iv) To expand their personal and interpersonal skills.

After 10 years, some 40 students, from 6 different institutions in within the FIRE network, received a FIRE certificate, signed by two professors and two non-academic industrial FIRE members who had evaluated the thesis work. It is implicit that such a procedure does fit in the CDIO approach, taking on account the non-academic members needs and the local and the societal context of each student. Since 2013 new initiatives have been implemented.

5.1. The FIRE Summer Schools

The Fire Summer Schools aim to promote cooperation on educational programs in refractories among the major institutions and companies of the sector. The goal is to review the fundamental principles, to define key challenges to be addressed by a younger generation of researchers and to open questions to move toward effective solutions. They create links between different scientific communities (ceramics, refractory manufacturers, metallurgy, mechanics, thermodynamics, instrumentation, sustainable development) and between industrial and academic research. They favor networking between young scientists and experimented experts. The participation of international professors and students is desired to promote scientific exchanges between the different continents. To date, 3 schools have been organized, for each the program were organized to facilitate the exchanges between participants and lecturers, and to integrate fundamental approaches, industrial needs, and new approaches on innovations.

1 Refractory Fire School, University of Orléans, France, June 17th - June 21st, 2013 (Fig. 3). The first aim was to review how to teach the fundamentals. A major consequence of this first FIRE School was to launch the FIRE Compendium Series of pedagogical books [15–18].
2 Ultra-refractories, Thermo-structural composites, Refractories: reactivity and corrosion, Politecnico di Torino, Italy, June 14th −15th 2019, organized under the aegis of the European Ceramic Society (ECeRS). This summer school was designed to enlarge the vision and the horizons of the students in to high temperature and ultra-high temperature ceramics and thermo-structural composites and develops a common language for better research and technological innovations. It positions the refractory researchers and gave them better visibility and gives the refractory industry its letter of nobility. Another important point was the recognition of our industry in the eyes of governmental agencies, granting subsidies.
3 Eco-design of refractories, Eco for Ecological, Economic, Eco-energetic. The School was organized both a face-to-face and virtual format. It started at RWTH Aachen University, Germany on June 28 and 29,2022, and then on the following day, at Tata Steel Plant in Ijmuiden, in the Netherlands, under the aegis of the European Ceramic Society (ECeRS). This third school on Eco-Design of Refractories has been designed with a CDIO approach, to integrate the fundamental knowledge, the industrial and economic needs as well as the future challenges to meet for refractories for steel steelmaking, in the coming years (CO_2 management and H_2 iron production).

Fig. 3. The cohort of participants at the first FIRE Summer School in Orleans (France).

The evening of the first day was devoted to a moment of discussion, brainstorming and conviviality between students, industrialists, and professors, during a poster session where each student had to present his research activities. On the third day the industrial case study presented and the visit of the steel plant were appreciated. The overall program was divided into 5 sessions, with 18 lecturers, 9 professors and 9 senior experts. The courses were memorized using video documents, and the face-to-face were extended with different videos to all registrants and pre-recorded presentations were inserted in virtual sessions during the breaks. A total of 105 participants registered, 72 face to face, 33 online registered participants, 29 students (17 face to face, and 12 on-line). Among the lecturers 16 were in face to face and two of them online. A special publication on ECeRS Open-Source Journal will follow.

5.2. The FIRE engagement to develop broad international projects

Based on 10 years common experience of cooperation, from 2005 to 2015 through FIRE network, some institutions (academics and industrials together) decided to move a step forward and to setup an European project to be submitted through the Marie Skłodowska-Curie Actions call (MSCA), named Innovative Training Networks dedicated to Excellent Science within European Framework research program (H2020 and then Horizon Europe), aim to train entrepreneurial, innovative and resilient doctoral candidates, able to face current and future challenges and to convert knowledge and ideas into products and services for economic and social benefit.

5.2.1. Innovative training network ATHOR (www.etn-athor.eu)

The financial support from the European Commission (3 737 239 €) was received from the European Union's Horizon 2020 research and innovation program under grant agreement no. 764987, to last form October in 2017 to March 2022 for the project entitled **A**dvanced **TH**ermomechanical multiscale m**O**deling of **R**efractory [19]. The project was to combine the efforts of 7 academic (AGH - Krakow - Poland, Montan Universität - Leoben - Austria, IRCER - Limoges - France, LAME-Orléans - France, RWTH - Aachen -Germany, ISISE - Minho - Portugal, Coimbra University - Portugal) and 8 industrial partners (Altéo Alumina, Imerys Refractory Minerals, Pyrotek Scandinavia AB, RHI-Magnesita, St-Gobain, TATA Steel, Safran Tech, FIRE). The ATHOR project, coordinated at the University of Limoges, focused on the training of 15 young researchers in multi engineering required fields for a better understanding of thermomechanical behavior of refractory linings. The research aimed at the design of more robust and reliable refractory linings, undertaken through the combination of advance numerical modelling with both small- and large-scale laboratory research, from the micro to the 10-m scale.

The cutting-edge research developed during the ATHOR project, ended in March 2022, has been widely disseminated. The 15 PhD students did present their work at prestigious international conferences with full publications in Rank A international journals. The net important societal result has been to provide well-trained professionals in the European refractory industry and at academic institutions.

5.2.2. Doctoral Network CESAREF (www.cesaref.eu)

The European Commission, early in 2020, announced its European Green Deal Plan to make Europe climate neutral by 2050, a plan to extend for 30 years, targeting among others energy intensive industries (steel-,glass- and cement-making). Refractory materials are key enablers for those industries. Already in 2020, a consortium conceived a new project entitled **C**oncerted **E**uropean action on **S**ustainable **A**pplications of **R**efractories. CESAREF was then granted a financial support of 4 103 866 €, in October 2022 for 4 years, to focus on the steelmaking industry still from the European Union 's Horizon Europe MSCA Doctoral Network, under a grant agreement no. 101072625, combining 15 beneficiaries (IRCER - Limoges - France, PIMM - Paris - France, CHEMENG/GEMME - Liege - Belgium, Montan Universität - Leoben - Austria, RWTH - Aachen -Germany, TU Wien - Wien - Austria, BAM - Berlin - Germany, Elkem, Imerys Aluminates, Calderys, RHI-Magnesita, Vesuvius, St-Gobain, TATA Steel, ArcelorMittal, Safran Tech) and 9 Associated Partners (Almatis, Pyrotek Scandinavia AB, Refratechnik Asia, Steuler, FIRE, Limoges University - France, Arts et Métiers Paris - France, Potsdam University - Germany, Koblenz University - Germany. This huge CESAREF consortium is coordinated at CNRS-IRCER in Limoges.

Fig. 4 presents the Overarching research and industrial objectives of CESAREF.

While creating new developments in the steelmaking and refractory industries, the network will train 15 highly skilled doctoral candidates capable of communicating and disseminating their acquired knowledge. CESAREF will create a core team across the European refractory value chain, accelerating the European refractory industries to drive towards sustainable materials and processes, as well as Net-Zero emission Steel production. This will help to create and secure sustainable employment in the European refractory and steelmaking industries.

5.3. FIRE Educative Platform. The use of E-learning and E-teaching courses for the education on refractories

Such a FIRE platform is hosted at the RWTH Aachen University. Cleary in academic as well as in industrial environment blended teaching methods and online learning have blossomed. At many universities worldwide traditional teaching classrooms have been turned into multiple learning activities during the Covid 19 pandemic [20,21]. Different ways of online teaching methods such as mini-lectures, discussion forums, class polls and quizzes have been developed in a short time. Up to now technically the remote learning tools for studies have been improved. Nevertheless, the function of universities as social places as well as the laboratory work must be considered for refractory engineers training. For this FIRE initiative to emerge the inputs of industrial manufacturers experts are needed. However, the FIRE academics have already in the last 6 years, tested the value of such '' Electronic LEArning Network On Refractories''. ELEANOR was part of the ATHOR project, organized with online webinars and face-to-face Refractory Training Courses (RTCs) meetings. These webinars and RTCs, given by the academic and industrial partners, have been recorded and uploaded to a Moodle™ platform. Moodle™ is a leading, open source, virtual learning environment and can be used in many types of teaching activities such as education, training, and development and in business settings. Here the implementation of "virtual classrooms" is highlighted. Different universities collaborate with Moodle™ and host a custom solution that features the same functions without the need for an external server. External participants can be invited and added to the classroom. To develop and extend a generation of different contents expert knowledge is added subsequently to each workshop or similar events as well as by partners specially involved in given topics [22].

5.4. The fire initiatives to develop data mining

The refractory industry has accumulated a significant amount of experimental results on industrial products as well as on laboratory made ones, provided by manufacturers, service providers, governmental agencies, and academics. It is time to consider the importance of data management and the value of data sharing to benefit from data mining efforts currently being attempted. In this context, the target is how the current required challenges in refractory innovations can be developed by linking the fundamentals to the digital tools, which could be critical for the new generations of refractory engineers. The following text from the GEMM group of Sao Carlos Federal University does help to define a roadmap (Fig. 5) for the refractory engineer for his present and future education (REPF).).

The new generation can't rely only on professional computer as the needs for the advances might be more urgent than their development and resources to acquire them. Fortunately, nowadays a broad amount of open-source software is available.

Nevertheless, their mastering demands a self-taught strategy. Aiming to make this learning process easier, Fig. 5 describes one of the many likely roadmaps to achieve the mastery of these tools by the Refractory Engineer of the Present and the Future (REPF).

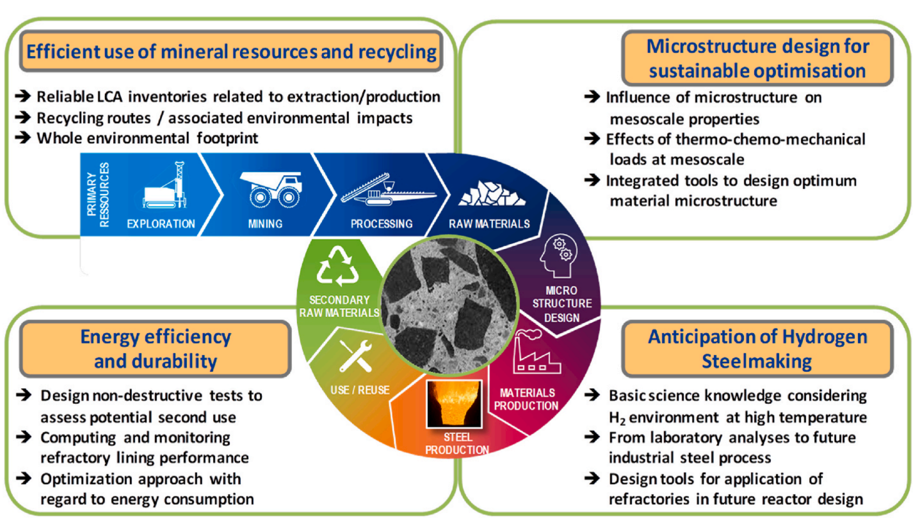

Fig. 4. Overarching research and industrial objectives of CESAREF within the circular economy challenges and using a multiscale approach.

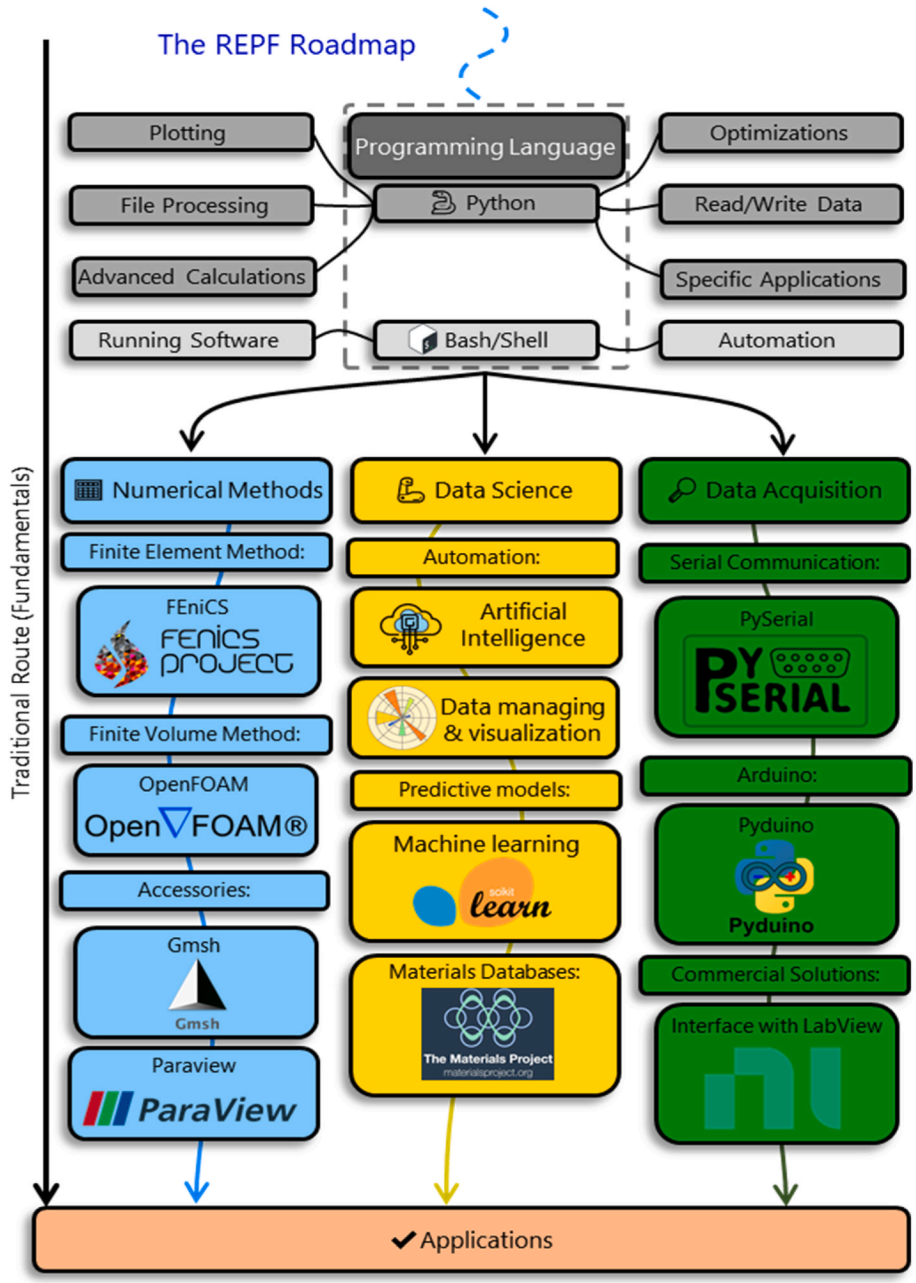

Fig. 5. The roadmap for the refractory engineer of the present and the future [23].

In this scenario, learning a programming language might be extremely helpful and even mandatory in some cases. Thus, the REPF roadmap starts with two distinct ones. Python is an interpreted, high-level object-oriented programming language, used in several applications, but mostly known by the scientific community [24]. It recently became one of the most used languages, given its versatility. Python is free, as are its various learning resources, such as books, courses, and videos. However, one should know that one of its main criticisms is that its computational costs on loops are high when compared to other compiled programming languages such as C++ [25].

The main applications for Python according to the roadmap are for preparing advanced plots (substituting expensive commercial software), data processing and advanced calculations (such as polynomial fittings, statistical analysis, time-series investigations, signal processing, etc.). Secondly, Bash (also known as "Shell") programming language is also highlighted as a valuable tool, as it is the most straightforward way to run software programs and automate tasks on the command line interface.

Having consolidated this first set of skills, three branches can be pursued depending on the user's profile, the problem at hand and the strategy of the solution. They are: (i) the numerical methods route, (ii) the data science track, and the (iii) data acquisition path.

The numerical methods route comprises a strong mathematical background. This is the price of migrating from commercial applications to open-source-based solutions. The learning curves are steeper and the understanding of the underlying theory is not optional. This directly affects the development timeline, but it can also lead to more in-depth analysis and innovative findings. Another aspect is that niche problems commonly found in the refractory field are usually not present in commercial software. Thus, in some cases, open-source programs are the only path.

Two distinct numerical methods are presented in the roadmap: the

Finite Element (FEM) and Finite Volume (FVM) methods, based respectively on the FEniCS platform and on the OpenFOAM software.

FEM is a numerical method for solving Partial Derivative Equations (PDE) based on searching for the best approximations of the analytical solution in a finite element function space, by multiplying the resulting PDE by a test function and integrating it over the domain of interest. This requires a mesh for spatial discretization. Several open-source applications can be used to create 2D and 3D meshes, but due to the easiness of using them and the possibilities of parametrization, the selected tool for the REPF roadmap would be Gmsh.

To solve the FEM problem, the FEniCS [26] platform is the selected tool of choice due to important aspects such as documentation, the size of the community using it and versatility. For the post-processing stage, both Python itself (via libraries such as Matplotlib and meshio) and Paraview can be successfully applied for advanced visualization of the results.

OpenFOAM [24] is the most versatile and comprehensive open-source software, with applications ranging from Computational Fluid Dynamics (CFD), to combustion analysis and even financial problems. Again, Gmsh, Python and Paraview can be used for mesh creation and visualization of results.

Using this package, complex problems on heat transfer while designing refractory lined equipment can be carried out starting from the geometry definition, followed by mesh preparation, solution of the system of equations, and finally post-processing. The analysis can also be focused on different aspects of the refractory field, ranging from the computation of effective properties to the simulation of a whole industrial process, such as steel cleaning by ceramic filters [27].

The complexity of industrial processes, especially the ones at high temperatures, depends on many different factors. In these cases, there are not many available commercial software that will manage directly with data, especially if the latter is recorded inappropriately. The engineer in these cases might look for programming languages, as in the case of Python, which provides a package of libraries to support the professional to analyze complex data problems.

A great set of packages would include Pandas, Numpy and Scipy for data preparation and structuring. The first one is an open-source library providing high-performance, easy-to-use data structures and data analysis tools [28]. Numpy and Scipy are a set of fundamental packages for scientific computing. Numpy provides algorithms for optimization, integration, interpolation, eigenvalue problems, algebraic equations, statistics, and many others [28].

For data visualization and dashboard design, Matplotlib or Seaborn is the most common libraries for creating static, animated and interactive visualization [28]. The understanding and usefulness of data are more remarkable when industrial information undergoes such analysis, especially when considering the development of smart systems, as it requires high-quality data to build predictive models as obtained by machine learning tools.

This leads to information streams that can successfully feed the data science algorithms, as well as characterize the behavior of the materials during applications, providing important information for the validation of numerical models.

All these three paths in Fig. 5 are closely interconnected and can provide innovative insights. One critical comment is that the full mastery of each of these individual tools might take years of experience, and what is proposed by this roadmap is to provide the basic knowledge to start and create connections with real experts in each of these areas. The low initial investment of these tools results in easier prototyping of solutions, which directly increases the likelihood of innovations. Furthermore, the fact that these open-source tools rely on a strong fundamental background makes the experience of working with them a rich environment for active learning. Nevertheless, we should never underestimate nor neglect the fundamentals of refractory engineering and the working experiences, which are unique to professionals in this area of knowledge and a key aspect to help analyzing the results.

The Python library that provides the most practical algorithms for machine learning is Scikit Learning. It can be applied for supervised and unsupervised learning, in the context of classification or regression problems. For instance, a regression problem for refractory application would be the lining thickness prediction in the basic oxygen furnace (BOF) according to the specific conditions of the process [29,30]. In the same environment, a classification example could be to identify cracks in refractory linings by image analysis.

First-principles generated databases of materials' properties are also an essential source of information, which can be queried by using Python APIs. One of the most extensive representations of this is Materials Project [31].

Finally, the data acquisition path can also be pursued. This set embodies tools that can be used with legacy versions of equipment through serial communication (using the PySerial library), custom state-of-the-art electronic platforms (via Pyduino) and even interaction with commercial solutions such as LabView. This can be used to develop custom-made laboratory equipment and even be scaled up to industrial applications.

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Lastly, the current worldwide efforts to minimize the environmental impacts of human activities add a new dimension to the area of refractories: besides sustaining their function in harsh environments, the high-temperature ceramics must also do so with minimal carbon footprint and the highest possible energy efficiency by diminishing thermal losses, for instance. This major target will not be attained without and holistic view as those provided by using these computing tools!

6. Conclusion

The key points of a refractory engineering program for the 21st century are summarized below:

1 Neither cognitive nor neural sciences can give a complete definition of human mind.
2 Mind involves consciousness and unconsciousness objective and subjective knowledges. Learning and teaching are then complex exercises, requiring to be performed with imaginative rationality.
3 All social political and industrial leaders must join forces with university's administrators and professors to conceive, design, implement and organize more proactive educative systems.
4 Refractory engineers must be present in a more engaging way to surf on the E-waves, E for Ecology, Energy, Economy, and Ethics.
5 Many of the seeds, needed to start reacting to the many signals being received daily, are planted. FIRE not being the only source.
6 For FIRE, with its same 20/20 vision it had in 2003, it is time to adept a global syllabus, mimicking the CDIO educative program described by Edward Crawley et al. [5] and adapting it for refractory graduate students making sure to include an evaluation procedure against accepted standards to provide the proper feedbacks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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