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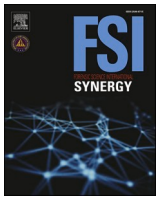

Interpol review of forensic management, 2019–2022

William P. McAndrew [a,*], Paul J. Speaker [b], Max M. Houck [c]

[a] Department of Finance and Economics, Dahlkemper School of Business, Gannon University, USA
[b] Department of Finance, John Chambers College of Business & Economics, West Virginia University, USA
[c] Global Forensic and Justice Center, Florida International University, USA

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ABSTRACT

This paper reviews and summarizes the forensic management literature from late 2019 to late 2022, covering laboratory strategic, tactical and operational decision-making, benchmarking, quality assurance, and managerial impacts from technological developments.

1. Introduction

"By failing to prepare, you are preparing to fail."

Benjamin Franklin

"If you don't know where you are going, you'll end up someplace else."

Yogi Berra

The 19th INTERPOL International Forensic Science Managers Symposium report for 2016–2019 recommended that the forensic sciences as a collective determine its own "path forward" by maintaining a culture of continuous improvement [1]. The authors offered a ten-year look in the rear-view mirror at the National Academy of Sciences' (NAS) 2009 report *Strengthening Forensic Science in the U.S.: A Path Forward* [2] with particular attention to the most recent three-year's publications in forensic management research. The 2019 Forensic Science Management report provided a perspective on both accomplishments in meeting the challenges of the NAS report and an accounting of the shortcomings from meeting the recommendations over the decade.

The 19th triennial report ended with a warning that led to the opening quotes in this 20th triennial report. If the forensic science community continues to concentrate on the "path forward" and embrace a culture of continuous improvement, the self-policing by the community may well hold off mandates from government outsiders regarding industry requirements. However, failure to set the strategy and develop the tactical and operational plans for continuous improvement will invite regulation from policymakers outside the world of forensics.

Shortly after the presentation of the review of the forensic science management literature at the 19th Triennial Forensic Science Managers Symposium, the National Institute of Justice released its report on the status and needs of forensic science laboratories in the United States [3]). This NIJ report provides suggestions on how to maintain the "path forward" and the public funding and educational investment required to stay on that path. The vision statement of the European Network of Forensic Science Institutes (ENFSI) offers a similar perspective on the needs of the industry moving forward [4].

The contributions to this literature reflect a global concern over the managerial decisions for forensic laboratories. This 20th triennial review includes contributions to forensic science management from 27 individual countries in addition to broad continental concerns. While past research in forensic science management was dominated by research from Australia/New Zealand, Europe, and the United States, the more recent research includes contributions from several African and Asian countries as well as representation from Central and South America.

This report begins with an overview of some of the themes highlighted in the forensic science management literature over the past three years, beginning with overviews of the details in the Office of Justice Programs report and the ENFSI vision statement. Together they provide a cogent outline to organize the research output from the past three years in forensic science management and highlight some key themes to discuss. This is followed by topics that fit with a framework of managerial decision-making. We review research tied to strategic initiatives, followed by tactical and operational decisions. Concluding remarks are

* Corresponding author.
E-mail addresses: mcandrew002@gannon.edu (W.P. McAndrew), paul.speaker@mail.wvu.edu (P.J. Speaker), mhouck@fiu.edu (M.M. Houck).

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offered in the final section.

2. Themes in the literature

Determining which research projects to include in the review of forensic science management is a fuzzy process since clear lines do not exist between research focusing on managerial decision making versus research with science and/or justice as the focal point. Beyond the more obvious business-related manuscripts, we have attempted to include research from the past three years that has a significant impact on strategic, tactical, or operational decision-making for laboratories. Since no clear line of demarcation exists, readers may feel that some impactful research may have been excluded, while other less deserving projects have been included. Indulge us for now and we encourage the reader to add their perspective to the future of forensic science management.

The United States status and needs report resulted from a mandate in the Justice for All Reauthorization Act of 2016 and called for a determination of the national forensic community's capital and personnel needs to deal with current case inflow and the growing backlog of casework [3]). The review took a systems approach, considering the direct needs of the laboratory with a consideration of the laboratory's relationship with the entire justice system and public stakeholders. Key topics included emergent technologies, education, training, research, and growing backlogs, particularly related to untested sexual assault kits (SAKs) and the opioid crisis.

The ENFSI updated vision [5] reflects the plans for the coming decade and addressed many of the same issues identified in the NIJ report. The ENFSI vision also follows a systems approach for the forensic laboratory, acknowledging the potential for an expanded role in law enforcement. The vision emphasized the role of emerging technologies that may expand the contribution that forensic intelligence offers to the administration of justice. The vision emphasized the importance of quality and competence from forensic science and the reliability of forensic results.

The NIJ report and the ENFSI vision each highlight the themes throughout the forensic management literature. The NIJ report included detailed analysis of the opioid crisis and the indeterminate size of the backlog of unsubmitted SAKs. The opioid crisis and more broadly the growth in emerging drugs has required more resources from the forensic laboratory, yet additional funding for the laboratories has not kept up with the growth in demand and a resource shift has occurred within laboratories [6–8]. Likewise, increased attention to the previously unsubmitted SAKs has put a strain on forensic laboratory resources [9]. These explosions in the demand for resources require updated strategic plans, followed by tactical and operational decisions to carry out those plans. Many of the publications over this period have examined alternative plans and methods to address the strains on system resources [10–13].

While the NIJ report suggests that nearly $1 billion in additional annual funding for state and local forensic laboratories is needed, there are other publications that suggest the forensic laboratory may be overfunded and more attention need be paid to the quality of analysis [14–18]. The call to maintain efforts for continuous improvement in quality represents a common theme in much of the research over this period. This includes strategic attention to bias and reliability (e.g. Refs. [19–21], while other quality assurance themes address the tactical and operational decisions with attention to total quality management systems [22,23] and Lean Six Sigma [11,24]. Additional attention to quality and consistency emphasizes the role of the International Organization for Standardization [10,24–27] and certification of individuals [28–32].

As highlighted in the ENFSI values position, attention must be paid to the forensic laboratory workforce. Some of the tactical decisions address investment in human resources [28,33–35]. Other studies examine the educational requirements for those entering the forensic science workforce (e.g., Refs. [3,28,36]. Following the NIJ report, which estimated that state and local forensic laboratories were understaffed by over 900 full-time equivalent personnel, a workforce calculator was developed to offer individual laboratories an independent estimate of any staffing shortfalls [37].

Finally, the role of technological developments is a theme found across areas of investigation. Following the dissolution of the National Commission on Forensic Science (NCFS) in 2017, the National Institute of Justice formed the Forensic Laboratory Needs Technology Working Group (FLN-TWG), which has produced several white papers reviewing new technologies looking at 3-D imaging (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021a), LC-MS-Based Forensic Toxicology Screening (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021b), Next Gen Sequencing (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021c), and Proteomic Mass Spectrometry (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021d). Other technological research includes consideration of technologies more broadly instituted across other industries such as machine-learning [13] and opportunities to enhance forensic intelligence using big data [38,39].

3. Business strategy

3.1. Systems and benchmarking

While much of the forensic science management research over the past three years looked at the strategic allocation of scarce resources, a common emphasis was a reminder that the forensic laboratory is part of the larger justice system and strategic planning must be centered in its role within the larger system. That begins with an examination of the mission and how the forensic laboratory serves justice in support of prosecution and exoneration [40,41]. Strategic planning around the mission of the laboratory within the justice system requires that the leadership of the laboratory guide the strategic plan with a focus on their mission [42]. This reliance on the connection between mission and strategy extends to all stakeholders within the justice system [43].

To begin formulating the optimal strategy a laboratory can begin to envision what is possible via benchmarking [44]. Project FORESIGHT offers a variety of benchmarks for forensic science managers with attention to productivity, timeliness, and financial management of limited resources [45]. Other potential sources for key benchmarking standards are available through organizational annual reports, grant reports, and various government publications [3,4,46–48].

As laboratory directors and their management team attempt to form optimal strategies to meet their mission, economic realities influence the scientific options available. Demands for laboratory services exceed the resources to meet requests for analysis and rationing must take place. Justice system leadership must maintain awareness of the economic concept of opportunity cost. That is, the cost of any activity can be measured in the opportunities forgone. As such, leadership must be aware of the costs as they relate to the benefits from any activity [49]. The severity of this economic problem of seemingly unlimited demands for services being met with too few resources is even more critical in small jurisdictions such as the Seychelles [50]. Because forensic laboratories do not generally operate in a competitive environment, forensic services may be limited to a political jurisdiction, which limits the scale of operations. Economics theory indicates that economies of scale improve the response to the economic problem of scarce resources through opportunities to lower the cost of each service as size increases. If specialized units are organized across jurisdictional lines, it may be possible to take advantage of these economies of scale [10].

Some suggestions for strategic direction broaden the measures for success to consider the indirect impacts from particular actions. For example, additions to the DNA database offer societal returns when the identification of suspects are obtained. However, there are indirect benefits through the very existence of the database through the deterrence of crime [51]. The reduction in recidivism has measurable impacts

that may be attributed to entries in the database [38]. Strategic considerations include novel systems to promote fairness, such as a voucher system to enable scientific analysis for all in an adversarial justice system [17].

3.2. Standards

Attention to the quality of forensic science remains at the forefront of considerations in the literature. The forensic laboratory "industry" through national and international organizations supports laboratories via research and uniform positions supporting strategies to maintain quality, ensure reliability of analyses, and promote confidence among all stakeholders. The International Forensic Science Alliance (IFSA) connects ENFSI, the American Society of Crime Laboratory Directors (ASCLD), National Institute of Forensic Science (NIFS ANZ), Academia Iberoamericana de Criminalística y Estudios Forenses (AICEF), Asian Forensic Sciences Network (AFSN), and Southern Africa Regional Forensic Science Network (SARFS). The alliance of these forensic laboratory networks establish standards for minimum required documents (MRDs) across forensic areas of investigation [4,46]. Uniformity in global practice includes the perception of quality as signaled through accreditation standards, which enhances the abilities of management to deliver forensic science analysis [52,53].

As the industry increases cooperative agreements on standards, accreditation and certifications provide signals of quality through independent verification of quality practice [29]. Commitment to uniform standards also provides the opportunity for continuous improvement. Initiating practices such as blind proficiency testing into the regular casework flow enables laboratories to learn about application of internal policies and procedures as well as individual performance [54]. The attention to quality offers a risk mitigation within the laboratory [55] and successes have applications which may be extended from the justice system to other practices [56].

3.3. Forensic intelligence

Forensic laboratory strategic planning includes continual reexamination of the role of forensic science in the administration of justice. The mission of the forensic laboratory directs management to maximize the value of forensic evidence [57]. Much of the analysis from the laboratory is treated as confirmatory only, missing the value that might be provided as part of up-front analysis following the commission of a crime. Laboratory leadership must overcome the bias of others within the justice system from an underestimation of the capabilities of forensic science in contributing to investigation [58].

A reconsideration of the forensic laboratory as an earlier participant with investigations enhances the ability of the justice system [59]. An expanded role for the forensic laboratory can move the laboratory from the confirmative role into a new role of forensic intelligence, where the coordination of evidence into the investigative stage offers linkages to leads across multiple investigations. Houck (ibid) provides an integrated forensic intelligence model (IFIM) to demonstrate the possibilities. One demonstration is the successful integration of a strategy using a forensic intelligence model using a Crime Gun Intelligence Center (CGIC) in Phoenix, Arizona [60].

Perhaps there is a stronger role for the forensic generalist or intelligence analyst to bridge the gaps between silos and expand the linkages between the forensic laboratory and police investigators [39,61]. Various alternative methods have been proposed to improve the role of forensic intelligence in investigation [62,63]. Empirical study of the success of the alternatives should determine best practices [64].

3.4. Technology

Technological developments appear at faster and faster rates. Although Moore's Law told the story of the growth of semiconductors, the empirical lessons of doubling time have been applied to a myriad of industrial technological growth. As new technologies are presented to the forensic sciences, strategic planning must consider if and when to adopt such technologies. Technological developments offer potential improvement in technique, turnaround time, data management, and support [65–67].

The integration of big data into forensic intelligence offers similar gains to those achieved in medicine, retail sales, and the financial sector [39]. Similarly, blockchain developments may simplify the management of evidence and chain of custody concerns (Sathyaprakasan et al., 2921).

To enhance the review of new technology and assist laboratory management in the consideration of new technologies, NIJ created FLN-TWG. This technology Working Group produced white papers on several new technologies and continues to assess emerging technology questions (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021a, 2021b, 2021c, 2021d). Elsewhere, return on investment reviews of new technology inform the industry of the economic value of new technologies [68].

3.5. Emerging drugs

Emerging drugs have led to record overdose deaths. The impact on the forensic laboratory comes in the form of direct effects on drug chemistry and toxicology, while indirect effects are experienced throughout the laboratory as a byproduct of shifting resources from other investigative areas to meet this growing demand [3]). The severity of the problem has been detailed beyond the academic frontier into the popular press with books appearing on best seller lists detailing the rise of P2P methamphetamine [69] and fentanyl [70].

The opioid crisis has brought to light the interconnectedness of public health, medical care, forensic laboratories, and medical examiner/coroner offices as a system of systems that requires coordination for the allocation of scarce economic resources. Research efforts to provide an economic evaluation of such resource allocation attempts to find the optimal investments to stem the growth in substance abuse and death [71]. Epidemiological and economic analysis offers detail on trends and economic impact to support the allocation of public funds for greater awareness of emerging trends. Without faster reaction times, the growing turnaround times for evidence processing may lead to deterioration of evidence and lost opportunities [72].

Several studies highlight the sentinel role that forensic laboratories and medical examiner/coroner offices play in identifying trends in controlled substance abuse. That sentinel role would be enhanced with improvements in the reporting of novel synthetic opioids by medical examiner and coroners [73]. Existing systems, such as the National Forensic Laboratory Information System (NFLIS) offer the linkage between systems for the identification of trends [74]. Uniform reporting standards would likely reveal a more severe crisis than current practices report. Forensic toxicologists play a key role in the identification of new psychoactive substances (NPS) to inform other laboratories and all other aspects of the public health and justice systems [75]. The enhanced role of toxicologists in the identification of emerging drugs may be realized through an increased role of outsourcing to independent laboratories [76]. Greater economies of scale for independent laboratories permit lower costs for the vast majority of medical examiner/coroner offices and lower the overall societal costs (ibid). The faster response from outsourcing contributes to public health and the delivery of justice [77].

A few studies offer some lessons from local experiences that contribute to strategic planning. The sentinel role that the forensic laboratory might play is detailed in a Houston case study on phencyclidine-impaired driving cases, highlighting how the laboratory can identify emerging trends to assist the justice and public health systems [78]. In other publications, greater anticipation of emerging trends can avoid greater problems down the road [79]. In Washington State, the legalization of marijuana use was anticipated to add over $300 million annually in taxes and fees. The State's forensic toxicology

laboratory eventually realized a case backlog exceeding 6,000 cases [80]. Additional funding for the anticipated driving under the influence of drug cases (DUID) should be anticipated when such laws are enacted.

3.6. SAK backlogs & de novo testing

The NIJ report devoted a great deal of attention to the large number of unsubmitted and untested SAKs [3]). Publications in this area included studies on the magnitude of the problem, alternative strategies for testing the backlog, societal costs and benefits, new technologies to assist in the testing, extensions to the testing of newly submitted SAKs, and communication with all stakeholders on the status of testing.

The magnitude of the problem of untested SAKs across jurisdictions in the United States is unclear (ibid), but rough estimates put the unsubmitted and untested SAKs in the range of 300,000 to 400,000 kts [81]. In the study of one jurisdiction, approximately 38% of SAKs were submitted to the State forensic laboratory with distance to the forensic laboratory being a main determinant whether a SAK would be tested [82]. The State forensic laboratory director suggested that greater cooperation between the forensic laboratory and law enforcement would lead to an increase in submissions moving forward but required strategic planning to overcome obstacles in order to succeed [40]. To make that happen significant resources and a multidisciplinary approach must be taken to reduce the backlog [83–86].

The societal gains from testing the backlog and "test all" policies provide benefits that far exceed the costs from expansion [68,87,88]. Those increased benefits come in many forms including reductions in future crimes. The size of the savings can be dramatic, particularly when the forensic analysis includes additions to the DNA database. In one study, the empirical analysis showed that a one percent increase in entries to the DNA database led to a 2.7% reduction in future assaults [38]. As backlogged SAKs are tested, a more complete picture of offenders emerges connecting them to additional crimes, both sexual assaults and other offenses (Campbell & Feeney et al., 2020). This suggests additional costs from not testing, where additional crimes are committed when the threat of DNA testing is absent [89].

Systemically, structural breakdowns contributed to the depth of the problem of unsubmitted and untested SAKs, which prompted strategic changes to amend the system [90]. It is suggested that resources be devoted to test all the untested SAKs, see what might be learned about the criminal justice system, and shed light on the damage to victims from the lack of follow up on their assaults [91]. Amongst the gains from test all programs is the forensic intelligence gained in the connection to other crimes [89], including profiles of sexual assault offenders and their tendencies [92]. These testing programs also provide an indication of the staffing needs moving forward as laboratory management gains evidence to support their claims for greater resources (Campbell, Fehler-Cabral et al., 2021). The early results from testing the backlog show that approximately half of the tested SAKs yield a Combined DNA Index System (CODIS) profile and half of those result in a hit [89].

The results of the backlog testing programs also lend support for testing of all *de novo* cases [93]. While testing all policies will require strategic planning for a significant increase in resources, questions emerge whether a prioritization of sample testing from SAKs offers a better solution. In one case study, a machine learning selection of samples was compared to expert selection of samples by sexual assault nurse examiners (SANEs) or sexual assault forensic experts (SAFEs) [13]. The case study revealed that machine learning was preferable to reliance on SANE or SAFE selections, yet a program of testing all samples provided justifiable economic results.

There are lessons to be learned from past behaviors that left so many untested SAKs and from the present programs attempting to uncover and test those kits. A recent collection of manuscripts on the past, present, and future of SAK testing outlines many of the lessons for the strategic planning by laboratories (Lovell & Langhinrichsen-Rohling (Eds), 2023). The look at past behaviors recognizes that systemic bias by police contributed to unsubmitted cases but stresses that bias within forensic laboratories contributed to the number of untested kits [94]. These biases shed a bad light across the system and destroyed the image of a victim-centered justice system [95].

Current efforts have attempted to make up for past mistakes through programs like the Sexual Assault Kit Initiative (SAKI) [96]. Systemic changes across the justice trail begin with proper collection of evidence and the training of SANEs [32,97] to include the victim with updates as investigations proceed [98].

Moving forward, as the laboratory makes plans for the future handling of SAKs, arguments for additional funding come from reviews of the societal return on investment (ROI) from testing [12]. The ROI offers funding bodies the economic rationale for the support of specific programs for legislative reforms and funding for SANE training, victim notification, and test all programs [99]. The lessons learned from cleaning up the backlog provide the rationale for national programs to avoid a recurrence of the problem [100]. Even with test all programs, laboratories must determine policies to prioritize the testing of samples [101] and continue to include all stakeholders in their programs [102–104] as they develop best practices (Langhinrichsen-Rohling & Lathan et al., 2023).

3.7. Bias, reliability, and other human factors

As an extension of interest in the quality of forensic science, researchers continue to explore the role of cognitive bias on the examination of evidence and the reliability of that evidence in courtroom testimony. In some jurisdictions, oversight boards have been created as a means to build trust among the public in the quality of forensic science [50,105]. Laboratories can provide internal policies by first recognizing the demands of the consumers of their output and anticipate stakeholder needs in forming policy [106].

Issues of bias are systemic concerns and assessment of problems and potential problems may be guided with the assistance of decision scientists [107]. Adoption of blind proficiency testing or programs such as Linear Sequential Unmasking can help to remove potential trouble spots from existing processes [21,108].

4. Tactical decision-making

Tactical decision-making is a shorter-term management view of an organization compared to strategic decision making. If a strategic goal of forensic science laboratories is to effectively support the criminal justice system broadly, the way a laboratory or laboratory system would go about achieving that long term goal would be in addressing shorter term tactical goals or issues. In this section, the tactical issues focused on will be quality assurance, human factors, technology, emerging drugs, and the new outlets for publication of developments in forensic science management and policy.

4.1. Quality assurance

Progress has been made to improve quality in forensic science especially since the 2009 NAS Report [2], yet forensic science still attracts criticism [18,44,109]. Although these criticisms vary and are decades if not centuries old in some cases [14], the 2009 NAS report helped to highlight the importance of quality assurance and continuous improvement to prevent miscarriages of justice. This is socially important, not only from an ethical standpoint, but also for the financial costs that some state governments or laboratories face to compensate those wrongfully imprisoned [110]. The money lost by forensic laboratories or governments associated with lawsuits addressing errors could go a long way towards improving quality that prevents mistakes [111]. This highlights the importance that any quality assurance program's cost should be viewed not only for its immediate cost and benefit, but also for the costs never seen correcting errors or mistakes that never occurred

[110,112]. Perfection may be impossible, mistakes might not always lead to injustices, and in many cases error rates are unknown, yet improvements in quality assurance programs that reduce error have the potential to show significant net benefits to laboratory budgets and society [112,113].

Although any single forensic science accreditation framework is imperfect, an evolving culture of continuous improvement has been embraced in the industry as an effective quality assurance tool [23,31,114]. The work of achieving and maintaining accreditation is challenging [111], yet third party accreditation is likely the best way to secure an effective quality assurance program. As a testament to this, the number of forensic laboratories that are accredited with ISO standards has increased over the last several decades [15]; Ross & Neuteboom, 2022). This has helped to boost the confidence level of stakeholders and customers of forensic science services and has facilitated inter-laboratory and cross-border collaboration [53,111,115]. Given the fragmented nature of forensic science laboratories in many countries [10,29], international accreditation standards may be a way to centralize standards in lieu of a national forensic science authority or a system supported by some stakeholders [18]; National Research Council, 2009), supporting the investigations of cross-border crimes [115].

Quality assurance can be supported in several other ways, many but not all of which are tied to accreditation standards. The following is a non-exhaustive list of quality assurance methods, the details of which can be found either in other sections of this review or in the supporting texts cited: lean six sigma or total quality management approach to improve turnaround time and efficiency [11,116,117]; Daku,2019 [118]; the use of a LIMS or case management system [10,111,119]; blind proficiency testing [20,27,30,53,54,108,120]; improved education or certification of forensic scientists and technicians [15,20,29–31,36,40,52,115,121]; other stakeholders [10,40,58]; improvements in organizational culture and stress reduction [19,23,116,122]; laboratory independence [17,18,52,120]; effective use of regulation [15,16,31,109]; improvements in evidence chain of custody and storage [10,119,123,124]; improvements in crime scene management and testing standards [10,15,125,126]; and reduction of biases and conflicts of interest [15–17,20,21,52,53,106–108,120,127,128].

4.2. Human factors

4.2.1. Cognitive bias

Television and the media often make forensic science appear infallible to the lay audience, known as the CSI effect, yet experts know that forensic science is far from perfect [16,17]. When humans make subjective decisions, there is an opportunity for bias and error [122]. Although machines, artificial intelligence (AI), and computers will eventually replace some human decisions and reduce cognitive errors, humans will likely always be involved in some way in forensic laboratory management [129]. Technology risk management, data integrity, coding bias, etc. will continue to be issues humans will be involved in managing or addressing [119,122,129,130]. Besides, an AI driven laboratory is not quite yet the reality we live in, and human bias is still an important issue facing forensic science today that leads to error and miscarriage of justice.

Forensic science laboratories are often organized as government entities or nonprofits, and as such, laboratory directors seek to maximize an objective other than profit. When the maximizing objective is centered towards policing or judicial outcomes, rather than an emphasis on science, bias and error can be introduced [39,45]. This is especially true if funding is tied to these policing and judicial outcomes [128]. Furthermore, since the cost of error is not often a part of a laboratory director's management calculus, as it might be for a hospital chief executive, incentive to minimize error is reduced [15]. The result is an environment where cognitive bias occurs leading to error and potentially wrongful conviction [15,16,20,39,52,107]; House of Lords, 2019 [55]; or wrongful liberty [112]. Cognitive bias can take the form of conviction bias or pro-police bias [17,106], contextual bias [107]; [55,128], gender bias [82], confirmation bias [107,128], a rape myth belief leading to inadequate levels of SAKs submission (Campbell & Fehler-Cabral, 2022), and funding bias [128] among other biases [130]. Additionally, bias at earlier levels of evidence processing can cascade into subsequent levels, and worse still this bias can add or multiply in a bias snowball effect as task irrelevant information from a variety of sources or levels interact with one another [20,107,131].

Most forensic laboratory directors believe that forensic science services should be based primarily on objective science and not supporting specific outcomes in the criminal justice system [42]. Therefore, to ensure the focus on sound science and reduce bias and by extension laboratory error, several solutions have been suggested. One solution is the use of a case manager who limits task irrelevant information. Whether an evidence match is found or not should be based on the evidence sample provided, not the case details provided by police [20,107]. Linear sequential unmasking in which case managers provided information sequentially and in certain evidence processing stages in order to limit task irrelevant information is a well-supported approach [20,21,52,127]. Another solution would be the creation of an independent laboratory system, a model example being the Houston Forensic Science Center [15,16,120]. By separating the laboratory's organizational power structure from that of police, a pro-police bias ought to be reduced [52,132]. Similarly, an independent private third-party laboratory paid for by the defense could provide needed balance, where a voucher system could be used [17]. This could help to balance any commercial conflicts of interest and better recognize the customers of forensic science [20,106]. Improved education on cognitive bias, public transparency, and regulation are also tools to reduce bias [3,15,16,20,106,128].

Accreditation requires proficiency testing to measure error for remedial purposes. However, most laboratories still practice open proficiency testing where technicians know they are being tested [53,108,120]. The test environment is likely to influence a person's behavior, so blind proficiency testing is preferred, where the analyst does not know a test is underway. Blind testing is more likely to reduce bias and fraud, measure the true error rate, and support making improvements when needed [120]; National Research Council, 2009; [108]. There are many challenges in creating a blind proficiency test program, yet the ability of these programs to reduce human errors will pay future dividends [120].

4.2.2. Stress

Another source of human decision error is the psychological effects of stress working in a forensic laboratory environment. Whether through high managerial expectations that work is error free, high workloads causing fatigue, or the vicarious trauma many laboratory employees experience due to working on disturbing cases, a proper response to stress by management is needed [3,19,122]. Stress can lead to either unbiased errors, or biased errors if there is pressure to get the "right" answer or avoid inconclusive decisions [19]. By creating a non-punitive system of risk management and error reporting, laboratory managers can help to reduce stress creating an environment for improved human judgment [122].

4.2.3. Education and training

Education and training support sound scientific decision-making, yet the 2009 NAS Report criticized the lack of standardized quality education and training programs in forensic sciences, and the resulting varied level of quality observed (National Research Council, 2009). Over a decade later, mandatory certification or education standards are still not required in most countries, yet some progress in forensic science education has been made often in the framework of accreditation. As an objective testament to this, some human resource data shows that the number of employees with a Master in Science (MSc) has increased, helping support employee promotions, and expected longevity of their tenure at a given laboratory [124]. There has also been continued

support for international education standards and certification to facilitate the investigation of cross-border crimes [31,115]. Discipline specific challenges and opportunities have been discussed in the literature, including in forensic anthropology [28], toxicology [34,75]; NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021b), DNA [3]), forensic intelligence [3]); SAKs submission and testing [85,96], and ballistics (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021a). There has also been support for education and training of forensic science stakeholders such as police and the legal community broadly [40,41,133], who in turn can then better support laboratories in achieving their mission of assisting the criminal justice system. As technology continues to advance there will be challenges in continuous education and retention of employees [33, 133]. To help reduce turnover, both training and proper job previews such as enhanced interviews or college internships should be used to educate current and future laboratory employees what the job entails and improve retention [33].

4.3. Technology

The management of technology in forensic science laboratories has advanced significantly since the 1980s and the more widespread adoption of LIMS [25,119]; U.S. Food and Drug Administration (FDA), 1984), helping support laboratories in meeting accreditation standards. The discipline specific forensic science methods developed, and the enormous amounts of computerized data created have required increasingly sophisticated technology to support laboratory operations. Advances in machine learning and robotics [13,129,134], blockchain [119,135], artificial intelligence [119], portable field tests [15,88,134], etc. have shown benefits many would only dream of in the 1980s. However, adoption of these new technologies has come with challenges [75]. This has put increased demand pressure on laboratories to perform at higher levels of volume [136]. This can then put strain on laboratory budgets [13,48,129] and creates pressure to justify the benefits and return on investment of new technologies [15]; NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021a,2021b, 2021c, 2021d; [6,135]. Further attention is needed when addressing questions of when to retire an old technology and introduce a new one [15], the importance of method validation [3,29,119,134,137–140], the broader effects of new criminal justice technology on society [15,43], and connecting technologies and data into a collaborative network [25].

4.4. Emerging drugs

The opioid epidemic exploded as an unprecedented public health crisis and has been a drain on already scarce forensic laboratory resources [71]. The next wave of the opioid crisis has arrived with the introduction of new and more dangerous synthetic drugs and new psychoactive substances (NPS), killing thousands of people annually (National Institute on Drug Abuse (NIDA}, 2022; [70]. The painful effect this has had on society through increased mental illness and homelessness [69], coupled with a competing drain on resources tackling COVID-19, has necessitated the development of new approaches to manage this emerging drug crisis [7,76]. Although forensic toxicology has expanded and improved over the last 40 years, a lack of reference standards on these new chemicals has limited the detection and quantification of toxicity [75]. New validated testing methods of increased sensitivity and specificity that meets regulation requirements in a cost-effective manner are therefore needed [134]; NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021b), which in turn will necessitate additional training of laboratory employees (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021b). Additionally, increased communication across laboratories and stakeholders in which national data on drug composition, toxicity, and overdoses is badly needed to better understand trends and gain broader access to drug reference standards [73]. One might suggest a CODIS or NIBIN style network for drug chemistry profiles that meets regulatory requirements with the added benefits of economies of scale. Updates to the Mass Spectral Library may fill this void [73]. As the landscape of the opioid epidemic continues to evolve [78], new and creative testing methods will be needed [77,134]; (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021b). This creativity is key, given the scarce laboratory resources in an environment of growing forensic service demands [37].

4.5. Journals

When *Forensic Science Policy and Management: An International Journal* ceased publication in 2017, it created a lack of venues for publishing articles about forensic science management. In 2019, *Forensic Science International: Synergy* was announced as the first Gold Open Access journal in the discipline; the journal set aside a portion of its domain for submissions on policy and management. Gold Open Access means that all the journal's articles are free to download in perpetuity. The Interpol Forensic Science Managers Symposium Organizing Committee requested that the research review papers produced for the Symposium be published in *Forensic Science International: Synergy* to allow for greater distribution and Interpol agreed. The articles are published after the Symposium as a Special Issue. In 2022, *Forensic Science International: Synergy* also began accepting Registered Reports, a pre-publication review process that focuses on methodology and sampling prior to any research being conducted. Also in 2022, *Wiley Wires: Forensic Science* began publication, accepting submissions on interdisciplinary topics and regulatory oversight, including those relating to management and policy. Many of the journal's articles are freely available.

5. Operational decisions

Operational decisions affect the day-to-day management of a forensic science laboratory and have shorter time horizons compared to strategic and tactical decision making. Operational decisions also often involve processes at lower levels in the organizational structure. In this section, the focus will be on forensic technologies, on the ground approaches to the emerging drug crisis, and the management of sexual assault kits.

5.1. Technology

5.1.1. Artificial intelligence and machine learning

Artificial intelligence (AI), machine learning, and now deep learning are growing ways that humans can augment their decision-making capacity in laboratory settings if properly executed. Google's DeepMind AI for example has predicted the 3D structure of nearly every one of the 200 million molecular cataloged proteins known to science and created an open source database of these structures to support research. The resulting acceleration of advancements that might be made in medicine, environmentalism, or biology are predicted to be groundbreaking [141]. Deep learning technology has applications in forensic science, for example in cataloging synthetic drugs, and then shared in an open-source network to fill a significant need in expanding toxicology reference standards [75]. Machine learning could be applied in decisions on what samples to prioritize for testing to receive the best return on investment, whether quantified in dollars or some other metric of return. In the case of sexual assault kits, there are more SAKs to be tested than current resources to conduct these tests, so knowing what samples yield the greatest match is desirable [13]. Machine learning has been shown to outperform expert human decisions in selecting probative samples, although testing of all SAKs is still recommended [8,13]. This technology is not risk-free, so proper risk management procedures to avoid errors in the system and potentially false positives or negatives is needed [119].

5.1.2. Blockchain and chain of custody

Movement of an evidence sample from one step in the forensic chain to the next requires proper packaging, documentation, and transportation to ensure the authenticity and integrity of the evidence expected by accrediting bodies and the courts [119,123,124]. Ensuring proper chain of custody is also a best practice to avoid civil lawsuits for lost or mishandled evidence [119]. The use of a LIMS is one way to help ensure chain of custody standards, so evidence can be accepted [56, 115]. As technology advances, so too must the chain of custody framework. Computer related crimes for example continue to grow, therefore a management information system for physical technology evidence with digital chain of custody documents and case data is needed. In many digital forensic laboratories, this system is deficient, and consequently courtroom outcomes can be affected [142].

Using a tamper proof method such as blockchain technology can support forensic laboratories broadly and has several noted benefits. The use of a permissioned blockchain ledger managed by a laboratory director or key employees can properly document evidence transactions, the personnel involved, the location of the evidence in the forensic chain, and ensure its validity in court. If evidence is or can be digitized, the blockchain can also be used in lieu of physically packaging and transporting evidence to other locations, which can reduce the likelihood of evidence loss or destruction, is eco friendly, saves time, and can save significant costs [135]. This could be especially beneficial to smaller and more remote jurisdictions that lack capacity and resources [50].

5.1.3. Networking technologies

Forensic science has the reputation of being a fragmented field of separate disciplines, which taken as a whole is also part of a collection of separate entities in the broader criminal justice system [2]; [44,105]. Bringing these separate entities together can help solve criminal cases though, so networking technology is of great importance [39]. Networking data and technology has grown since the broad introduction of computerized LIMSs in the 1980s. Communication and an ability to collaborate within laboratories and across criminal justice stakeholders has always been important, and technology has served to support this [48]). Linking information helps automate workflow, and has improved the capacity to either solve crimes or create forensic intelligence that supports predictive policing. Integration with public data for instance has allowed for regional investigations to leverage larger datasets, such as the CODIS dataset, to then be able to solve national or international cross-border, serial, and volume crimes more effectively in ways not possible in decades past [25,26]. Challenges to networking technology exist, such as the adoption of a common forensic science language and standards across jurisdictions, but accreditation has served to overcome some of this hurdle [53,115]. The location of servers, regulations on when to include data into national databases, or how to handle data created by blind proficiency testing, etc. are further challenges worth overcoming [15,26,108]. The software integration of LIMS into benchmarking data systems such as FORESIGHT have also helped laboratories better understand where they stand compared to their peers in order to take actions towards continuous improvement [6].

DNA databases have received much attention due to their potential in helping reduce the dramatic SAKs backlog experienced in many jurisdictions and for the significant return on investment that testing has shown [12,32,68,94–104,136,143–145]. Forensic scientists can now enter sexual assault case data into a LIMS, and both add to and use databases such as CODIS to find a matching DNA profile quickly and support police investigations and intelligence [85]. With the ability to conduct familial searches or use trace evidence, the usefulness of DNA databases has grown further [10,48]. The number of serial rapists in these databases shows support that funding for more aggressive SAKs testing is warranted. An arrested person's awareness that their DNA is entered into a database has also shown a deterrent effect on future crime as criminals respond to the increased likelihood of getting caught, i.e. the elasticity of crime [38,51,57]. As the size of the database grows this effect may grow as the benefits of economies of scale take place [88].

Other databases such as the NIBIN database and related Evofinder and ShotSpotter technology have also created networks to supported investigations in the growing gun crime epidemic by helping to bring together ballistics forensic information with police data [26,146]. A similar system with shared toxicology data and trends might also aid in combating the surge in emerging synthetic drugs [73].

5.1.4. Other technologies

There are several other technologies highlighted in the forensic science management literature over the last few years. Validation studies on portable field tests such as the ANDE™ FlexPlex Rapid DNA system or near infrared technology drug tests for instance have shown great promise [134,147]. As these portable field tests are validated and shown to produce reliable results, the decentralization of forensic science has the potential to reduce testing turnaround times and laboratory backlogs, as well as help prioritize further laboratory testing [134]. If the results of these portable field tests are approved to be included in national databases such as the National DNA Index System (NDIS), the benefits to investigators can grow exponentially [147]. Other new notable technologies evaluated are 3D imaging systems for firearms and toolmarks, new toxicology screening methods, next generation sequencing for DNA analysis, and new testing for biological fluid identification (NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021a,2021b,2021c,2021d). The reader may know of many other new and exciting technologies discussed over the last three years not included in this review.

5.2. Emerging drugs

As the opioid epidemic grows, the on-the-ground approaches to the crisis also need to evolve [70]. Portable field screening tests using technology such as ion mobility spectrometry or near infrared technology have shown promising benefits [73,134]. Not only do these new approaches give information quickly to investigators, they also potentially reduce evidence submission to laboratories for validation. As laboratory budgets have not grown with the increasing demand for forensic services and forensic laboratories are asked to "do more with less", reduced drug evidence processing time in forensic laboratories is also badly needed. Direct Analysis in Real Time-Mass Spectrometry (DART-MS) and liquid chromatography-mass spectrometry (LC-MS) with improved sensitivity and specificity are technologies that may provide more timely results that the traditional immunoassay toxicology tests, that can in turn more accurately identify the specific drug(s) involved in an overdose [73]; NIJ Forensic Laboratory Needs Technology Working Group (FLN-TWG), 2021b). The so-called "organ-on-a-chip" using *in vitro* human cell cultures is another new alternative to existing toxicology tests that regulators and pharmaceutical drug companies have shown interest in as an alternative to the less sustainable laboratory animal testing [77]. A cost-benefit analysis of all these technologies and consideration of equipment leasing options is recommended.

The resource drain that the opioid crisis has put on laboratories has also created shortages of laboratory staff and pathologists. The NIJ 2019 report estimated that there was a staffing deficit of over 900 positions [3]). This shortage of labor in laboratories often then leads to backlogs and increased turnaround time, to the detriment of case investigations. Improved education and increasing new graduate pipelines, trainings, positive salary adjustments, etc. can improve labor availability and motivation in the forensic laboratory to help address this staff shortage [10,33,37,75,76].

The opioid epidemic is about much more than drug testing and solving crimes, and opioid prevention or medical care can go a long way supporting forensic laboratories manage caseloads. This public health crisis is also a human epidemic of despair, mental health collapse, and

unemployment among other intertwined comorbidities [69]. Improved communication and partnerships with hospitals, regulators, and police are needed to help those afflicted and to track epidemiological trend data [71]. Syndromic surveillance and epidemiological modeling can aid in recognizing outbreaks of drug outbreaks to better prepare drug treatment programs, syringe exchanges, or prioritize geographical locations of naloxone [73]. These models can also potentially predict future demographic trends on who the users of the future will be, to improve targeted prevention efforts [78].

5.3. SAKs

In the United States, several hundred thousand SAKs remain untested or even unsubmitted for testing [68,94]. Whether due to a police officer's reluctance to submit these kits for testing, or the backlogs experienced in many laboratories due to resource constraints, the result for many victims is "justice denied" [82,132]. With the recent #MeToo movement and negative media attention on untested SAKs stored in many jurisdictions as long as decades [148], and worse SAKs destroyed or degraded either intentionally [149] or unintentionally [150], the public's demands to do something has grown [85].

DNA databases have shown enormous social benefits and have the ability to magnify the value of testing SAKs. Investigators can now more easily find DNA profile matches to not only solve a given rape case, but can also detect patters of serial rapists, solve cold cases, and exonerate the innocent [136]. The scope of a serial offender's crimes are also found to be more complete using SAKs testing and DNA databases compared to that found in evaluating criminal case files [143]. Even if the statute of limitations has expired on a given case, testing a SAK can still provide value in supporting the investigation of other crimes especially if the perpetrator is a prolific offender (Campbell et al., 2019). As DNA database systems expand, the value to investigators expands also, leading to increased evidence submission and for some laboratories increased backlogs. Much like a swinging pendulum, as the backlog grows, police may be more hesitant to submit a SAK if the time it takes to receive test results grows. Efficient and timely processing of evidence should then be a goal of every forensic laboratory that tests SAKs, so rape victims are not denied justice through low police submission rates [40]. Timely SAK testing can also reduce recidivism if serial offenders are removed from society before they commit additional sexual assaults or other crimes [57]. This reduces future resource use by police and forensic laboratories if future crime is reduced, with a societal return on investment estimated to be very large for every SAK tested [68,101].

The economic problem is one of scarcity, or that society has unlimited wants but limited resources to fulfill those wants. Tradeoffs and prioritization of testing certain SAKs then may be a reality for forensic investigators, even if testing all SAKs is a worthy secondary goal. Prioritization based on case characteristics such as victim age or weapon use may produce more probative results [91]. Machine learning models have also shown to produce more probative results compared to human experts choosing which SAKs to test based on characteristics of the SAK [8,13]. Prioritization of police submission of SAKs and the prioritization of collection of evidence from a victim however has been shown to be problematic. In a recent study that looked at four separate geographic jurisdictions and what predicted SAKs submission, geography rather than case characteristics was the primary predictor of submission, and only one quarter of SAKs were submitted for testing on average. If public safety is the priority, evidence-based submission protocols rather than emotions and idiosyncratic police perceptions should determine SAKs submissions [151]. The independence of laboratories and police in the decision to submit a SAK could also reduce bias in submission practices.

There is a clear need for reform in the handling of SAKs submission and testing [99]. Continued innovations will be needed, such as in Rapid DNA portable field tests [88]. Cost-benefit analysis can help prioritize resource use in laboratories or any future legislative proposals [12,49,97,100]. Many changes have been suggested, such as mandatory testing legislation [132,151], victim-centered police training, encouraging victim participation [85], improved LIMS use to track SAKs, not only for a laboratory but for a victim who's SAK holds great emotional value [83,95,98,102,104], increased resource availability, and continuous testing to maintain skillsets of a laboratory and technician in techniques such as trace evidence [40]. Improved leadership, cross-discipline and institution partnerships [90,103], recognition of economies of scale and potential rural versus urban issues are additional challenges to overcome [32,68,143]. The National Sexual Assault Kit Initiative (SAKI) started in 2015 is a great example of a grant program administered by the U.S. Bureau of Justice and Assistance that is working with jurisdictions on many of these challenges and goals, helping to safeguard justice for victims and increase public safety [83,84,96,99,102].

6. Conclusion

Numerous reports from a growing number of countries around the world indicate an increased awareness of the changing needs of the forensic industry. The usual culprits for lowered effectiveness and efficiency are blamed, such as insufficient funds, staffing, and high submission rates. Management approaches such as lean six sigma, mandatory credentials, and accreditation standards have been suggested as possible solutions. Additional issues loom, however, that will challenge forensic managers and their agencies. The explosion of digital evidence as a forensic discipline and its diverse deployment across agencies is poised to outstrip resources unlike anything seen since the advent of forensic DNA analysis. Artificial intelligence and machine learning show promise to help with decision-making but it is important to remember that an algorithm is only as objective as its authors. The integration of rapid DNA and next generation sequencing into operational casework will create a platform shift that will be enormously disruptive but hold the potential to revolutionize forensic biology and greatly reduce backlogs. As stated in previous reviews, embracing leadership and a shared vision through organizations such as the ENFSI or the NIJ's forensic needs technology working group (FLN-TWG) continue to allow forensic science to create its own path forward rather than take legislative orders requiring forced changes. These and other topics will no doubt be covered in the next management review of this symposium.

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